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Zhou et al.

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(54) CONTROL CHANNEL ELEMENT INDEXING FOR UPLINK TRANSMISSION

(71) Applicant: **KONINKLIJKE PHILIPS N.V.**, Eindhoven (NL)

(72) Inventors: **Hua Zhou**, Vienna, VA (US); **Esmael Hejazi Dinan**, McLean, VA (US); **Ali Cagatay Cirik**, Chantilly, VA (US); **Yunjung Yi**, Vienna, VA (US); **Hyoungsuk Jeon**, Centreville, VA (US); **Hyukjin Chae**, San Diego, CA (US)

(73) Assignee: **Koninklijke Philips N.V.**, Einhoven (NL)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **18/110,526**

(22) Filed: **Feb. 16, 2023**

(65) **Prior Publication Data**

US 2023/0199772 A1 Jun. 22, 2023

Related U.S. Application Data

(63) Continuation of application No. 17/519,102, filed on Nov. 4, 2021, now Pat. No. 11,617,164, which is a (Continued)

(51) **Int. Cl.**
H04W 72/20 (2023.01)
H04W 16/14 (2009.01)

(52) **U.S. Cl.**
CPC ***H04W 72/20*** (2023.01); ***H04W 16/14*** (2013.01)

(58) **Field of Classification Search**
CPC H04W 72/20; H04W 16/14
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2009/0201863 A1 8/2009 Pi
2011/0045860 A1 2/2011 Nam et al.
(Continued)

FOREIGN PATENT DOCUMENTS

WO 2021/063872 A1 4/2021

OTHER PUBLICATIONS

3GPP TS 38.211 V15.5.0 (Mar. 2019); Technical Specification; 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Physical channels and modulation; (Release 15).

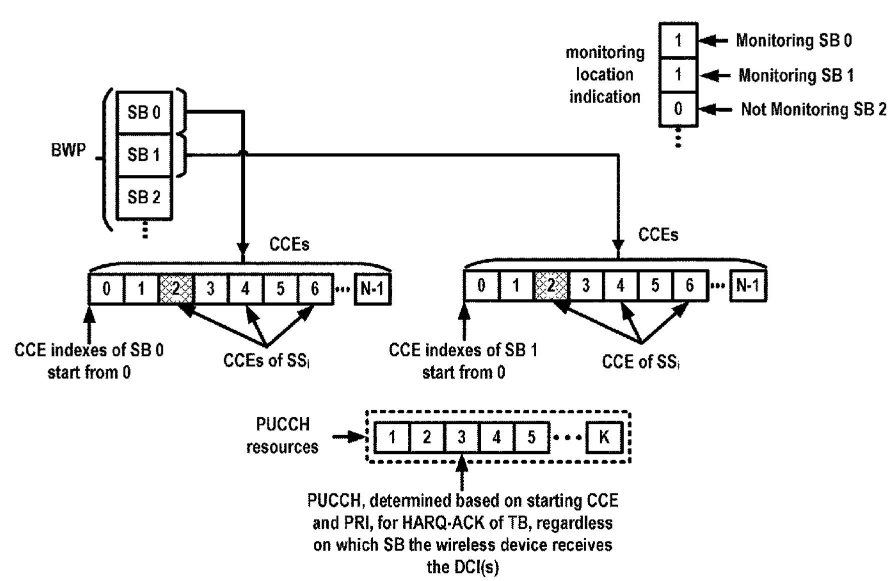
(Continued)

Primary Examiner — Jasper Kwoh

(57) **ABSTRACT**

A base station transmits, to a wireless device, configuration parameters of a control resource set in a bandwidth part (BWP), and the control resource set includes resource block (RB) sets of the BWP. The base station transmits a control information via one or more control channel elements (CCEs) of first CCEs within a first RB set of the RB sets. The base station receives, from the wireless device, a signal via an uplink resource based on an index of a CCE of the one or more CCEs of the first CCEs. The index is determined based on first index values, of the first CCEs within the first RB set, starting from a same initial value as that of index values of CCEs within each respective RB set of the RB sets.

17 Claims, 34 Drawing Sheets



Related U.S. Application Data

continuation of application No. PCT/US2020/058814, filed on Nov. 4, 2020.

(60) Provisional application No. 62/930,130, filed on Nov. 4, 2019.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2014/0133370	A1*	5/2014	Chen	H04W 72/23 370/280
2016/0150508	A1	5/2016	Golitschek Edler Von Elbwart et al.	
2019/0141679	A1	5/2019	He et al.	
2019/0297618	A1*	9/2019	Yang	H04L 5/0055
2019/0313400	A1	10/2019	Farag et al.	
2020/0280985	A1*	9/2020	Ijaz	H04W 72/21
2022/0368489	A1*	11/2022	Grant	H04L 5/001

OTHER PUBLICATIONS

3GPP TS 38.212 V15.5.0 (Mar. 2019); Technical Specification; 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Multiplexing and channel coding; (Release 15).
3GPP TS 38.213 V15.5.0 (Mar. 2019); Technical Specification; 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Physical layer procedures for control; (Release 15).
3GPP TS 38.214 V15.5.0 (Mar. 2019); Technical Specification; 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Physical layer procedures for data; (Release 15).
3GPP TS 38.300 V15.5.0 (Mar. 2019); Technical Specification; 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; NR and NG-RAN Overall Description; Stage 2; (Release 15).
3GPP TS 38.321 V15.5.0 (Mar. 2019); Technical Specification; 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Medium Access Control (MAC) protocol specification; (Release 15).
3GPP TS 38.331 V15.5.0 (Mar. 2019); Technical Specification; 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Radio Resource Control (RRC) protocol specification; (Release 15).
3GPP TSG RAN WG1 Meeting #98bis; Chongqing, China, Oct. 14-20, 2019; Title: RAN1 Chairman's Notes.
R1-1909987; 3GPP TSG-RAN WG1 Meeting #98bis; Chongqing, People's Republic of China, Oct. 14-20, 2019; Agenda Item: 6.2.1.2; Source: Ericsson; Title: Support for transmission in preconfigured UL resources in LTE-MTC; Document for: Discussion and Decision.
R1-1910012; 3GPP TSG RAN WG1 Meeting #98b; Chongqing, China, Oct. 14-20, 2019; Agenda Item: 7.2.2.2.5; Source: Spreadtrum Communications; Title: Wideband operation in NR-U; Document for: Discussion and decision.
R1-1910049; 3GPP TSG RAN WG1 Meeting #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda Item: 7.2.2.2.5; Source: Huawei, HiSilicon; Title: NRU wideband BWP operation; Document for: Discussion and Decision.
R1-1910158; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14- 20, 2019; Agenda Item: 7.2.2.2.5; Source: Lenovo, Motorola Mobility; Title: Wideband operation for NR-U; Document for: Discussion & Decision.
R1-1910208; 3GPP TSG RAN WG1#98bis; Chongqing, China, Oct. 14-20, 2019; Source: vivo; Title: Discussion on wideband operation in NR-U; Agenda Item: 7.2.2.2.5; Document for: Discussion and Decision.
R1-1910463; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda item: 7.2.2.2.5; Source: Samsung; Title: Wideband operation for NR-U; Document for: Discussion and Decision.
R1-1910600; 3GPP TSG RAN WG1 #98-bis; Chongqing, China, Oct. 14-20, 2019; Source: Fraunhofer HHI, Fraunhofer IIS; Title: Wideband operation for NR-U; Agenda item: 7.2.2.2.5; Document for: Discussion and Decision.
R1-1910603; 3GPP TSG RAN WG1 Meeting #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda item: 7.2.2.2.5; Source: Nokia, Nokia Shanghai Bell; Title: On wideband operation in NR-U; Document for: Discussion and Decision.
R1-1910644; 3GPP TSG RAN WG1 Meeting #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda Item: 7.2.2.2.5; Source: Intel Corporation; Title: Wideband operation for NR-unlicensed; Document for: Discussion/Decision.
R1-1910763; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda Item: 7.2.2.2.5; Source: Sony; Title: UL wideband operation for NR Unlicensed; Document for: Discussion/Decision.
R1-1910794; 3GPP TSG RAN WG1 #98b; Chongqing, China, Oct. 14-20, 2019; Source: OPPO; Title: Wideband operation for NR-U; Agenda Item: 7.2.2.2.5; Document for: Discussion and Decision.
R1-1910823; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda Item: 7.2.2.2.5; Source: LG Electronics; Title: Wide-band operation for NR-U; Document for: Discussion and decision.
R1-1910932; 3GPP TSG RAN WG1 Meeting #98bis; Chongqing, China, Oct. 14-20, 2019; Source: Sharp; Title: Wideband operation and UL/DL indication for NR-U; Agenda Item: 7.2.2.2.5; Document for: Discussion and Decision.
R1-1910943; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda Item: 7.2.2.2.5; Source: InterDigital, Inc.; Title: NR-U Wideband operation; Document for: Discussion, Decision.
R1-1910951; 3GPP TSG-RAN WG1 Meeting #98bis; Chongqing, China, Oct. 14 - 20, 2019; Agenda Item: 7.2.2.2.5; Source: Ericsson; Title: Wideband operation for NR-U; Document for: Discussion, Decision.
R1-1910997; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Source: ETRI; Title: Further views on wideband operation for NR-U; Agenda Item: 7.2.2.2.5 Wide-band operation; Document for: Discussion/Decision.
R1-1911056; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda item: 7.2.2.2.5; Title: Wideband operation for NR-U .; Source: MediaTek Inc .; Document for: Discussion.
R1-1911101; 3GPP TSG RAN WG1 Meeting #98bis; Chongqing, CN; Oct. 14-Oct. 20, 2019; Agenda tem: 7.2.2.2.5; Source: Qualcomm Incorporated; Title: Wideband operation for NR-U; Document for: Discussion and Decision.
R1-1911164; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Source: NTT DOCOMO, INC.; Title: Wide-band operation for NR-U; Agenda Item: 7.2.2.2.5; Document for: Discussion and Decision.
R1-1911242; 3GPP TSG-RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Agenda Item: 7.2.2.2.5; Source: Panasonic; Title: Wideband operation in NR unlicensed; Document for: Discussion, Decision.
R1-1911314; 3GPP TSG RAN WG1 #98bis; Chongqing, China, Oct. 14-20, 2019; Source: WILUS Inc.; Title: Wideband operation for NR-U; Agenda item: 7.2.2.2.5; Document for: Discussion/Decision.
International Search Report and Written Opinion of the International Searching authority mailed Feb. 15, 2021, in International Application No. PCT/US2020/058814.
R1-1809144; 3GPP TSG RAN WG1 Meeting #94; Gothenburg, Sweden, Aug. 20-24, 2018; Source: NTT DOCOMO, INC.; Title: Maintenance for carrier aggregation and bandwidth parts; Agenda Item: 7.1.3.4; Document for: Discussion and Decision.
R1-1720380; 3GPP TSG RAN WG1 Meeting 91; Reno, Nevada, Nov. 27-Dec. 1, 2017; Agenda Item: 7.3.2.4; Source: NEC; Title: Resource allocation for NR PUCCH; Document for: Discussion and decision.
R1-1804805; 3GPP TSG RAN WG1 Meeting #92bis; Sanya, China, Apr. 16-Apr. 20, 2018; Agenda item: 7.1.3.2.4; Source: Qualcomm

(56) **References Cited**

OTHER PUBLICATIONS

Incorporated; Title: Remaining issues for resource allocation for PUCCH; Document for: Discussion/Decision.

* cited by examiner

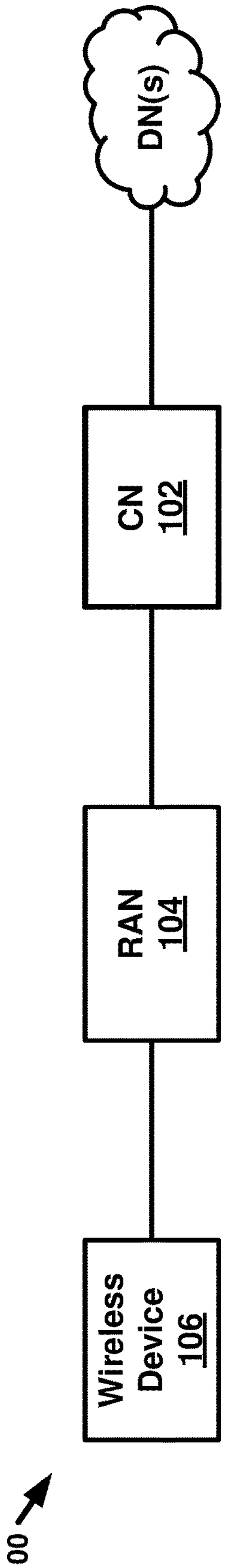

100
Wireless Device 106
RAN 104
CN 102
DN(s)

FIG. 1A

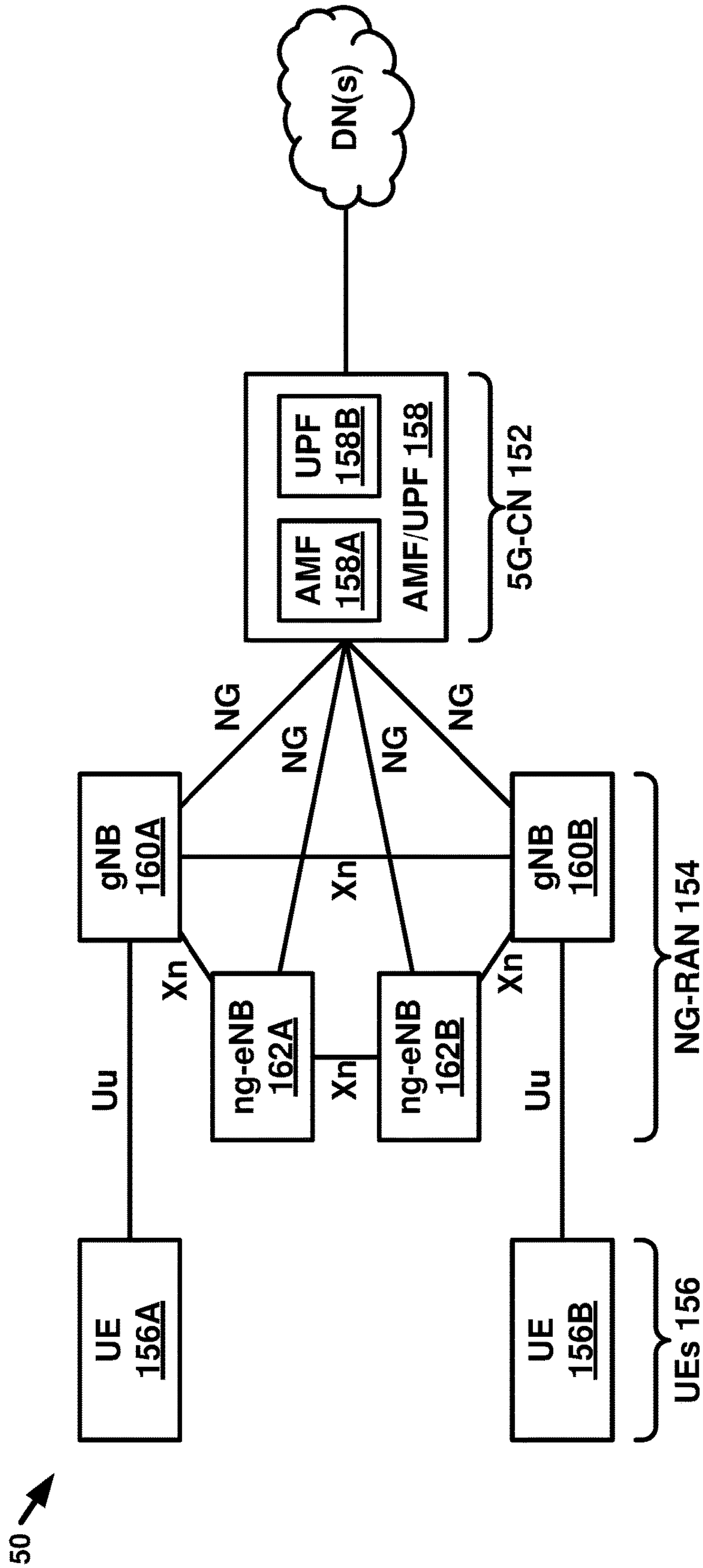

150
UE 156A
UE 156B
UEs 156
Uu
Uu
gNB 160A
gNB 160B
ng-eNB 162A
ng-eNB 162B
Xn
Xn
Xn
Xn
NG
NG
NG
NG
NG-RAN 154
AMF 158A
UPF 158B
AMF/UPF 158
5G-CN 152
DN(s)

FIG. 1B

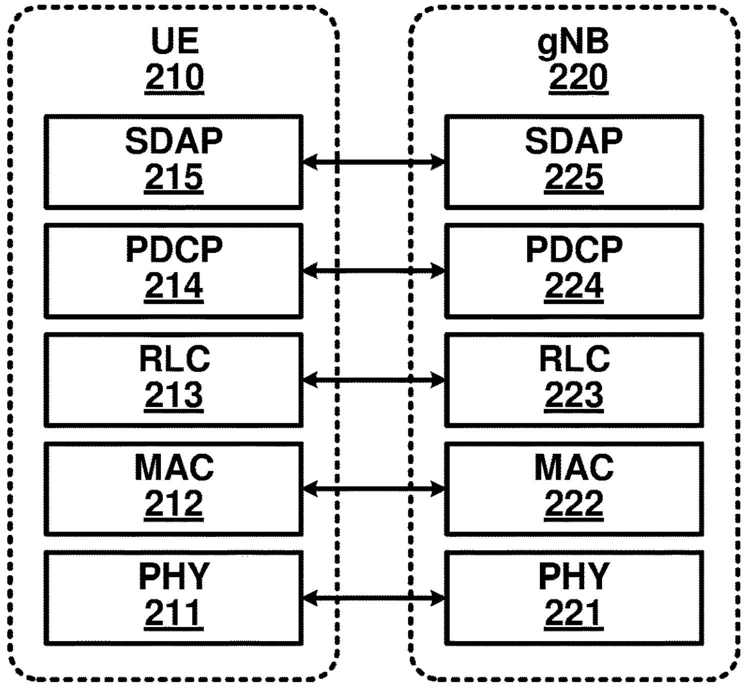

UE
210
SDAP
215
PDCP
214
RLC
213
MAC
212
PHY
211
gNB
220
SDAP
225
PDCP
224
RLC
223
MAC
222
PHY
221

FIG. 2A

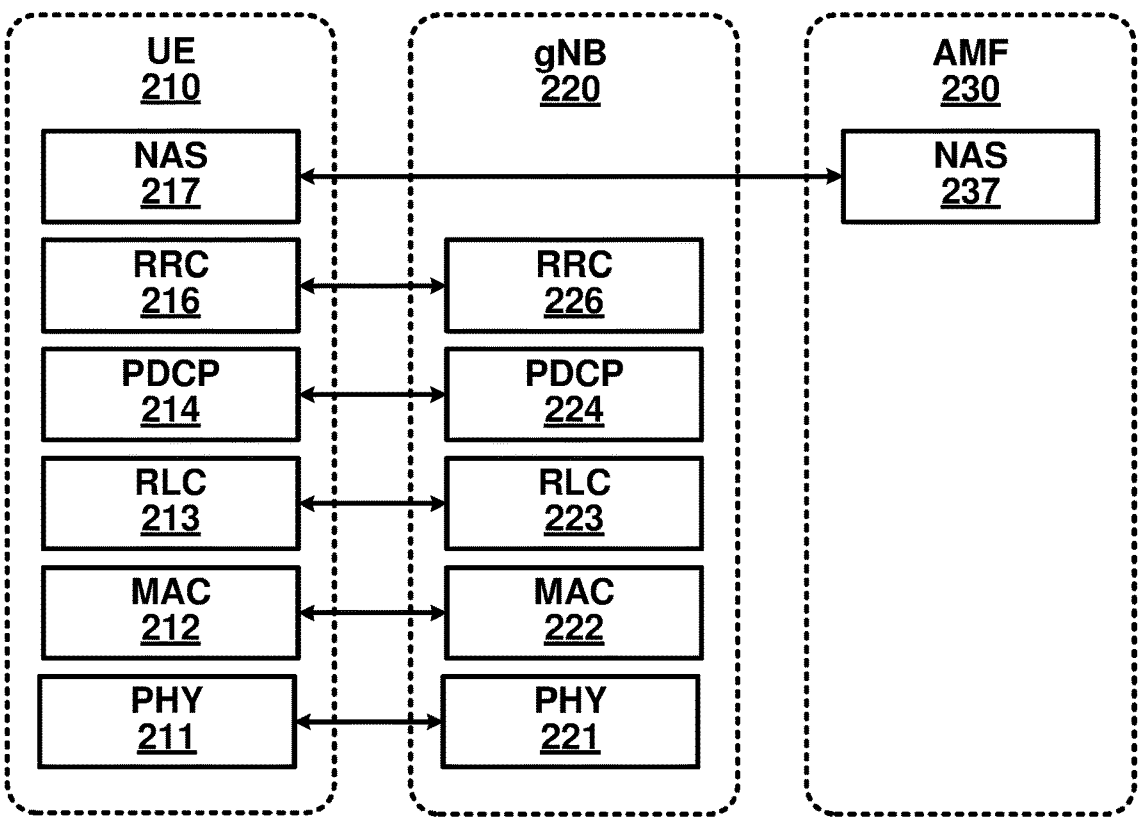

UE
210
NAS
217
RRC
216
PDCP
214
RLC
213
MAC
212
PHY
211
gNB
220
RRC
226
PDCP
224
RLC
223
MAC
222
PHY
221
AMF
230
NAS
237

FIG. 2B

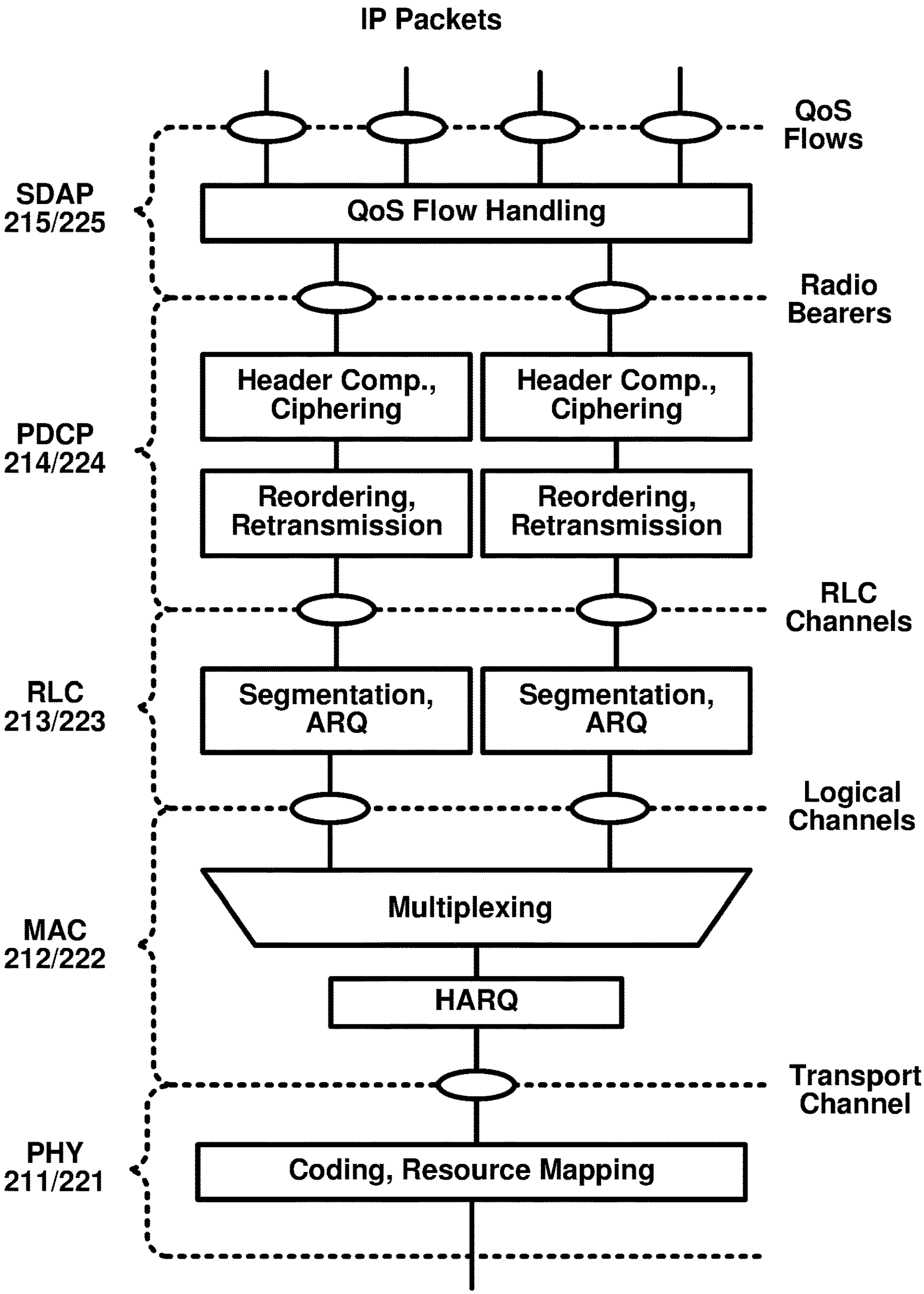
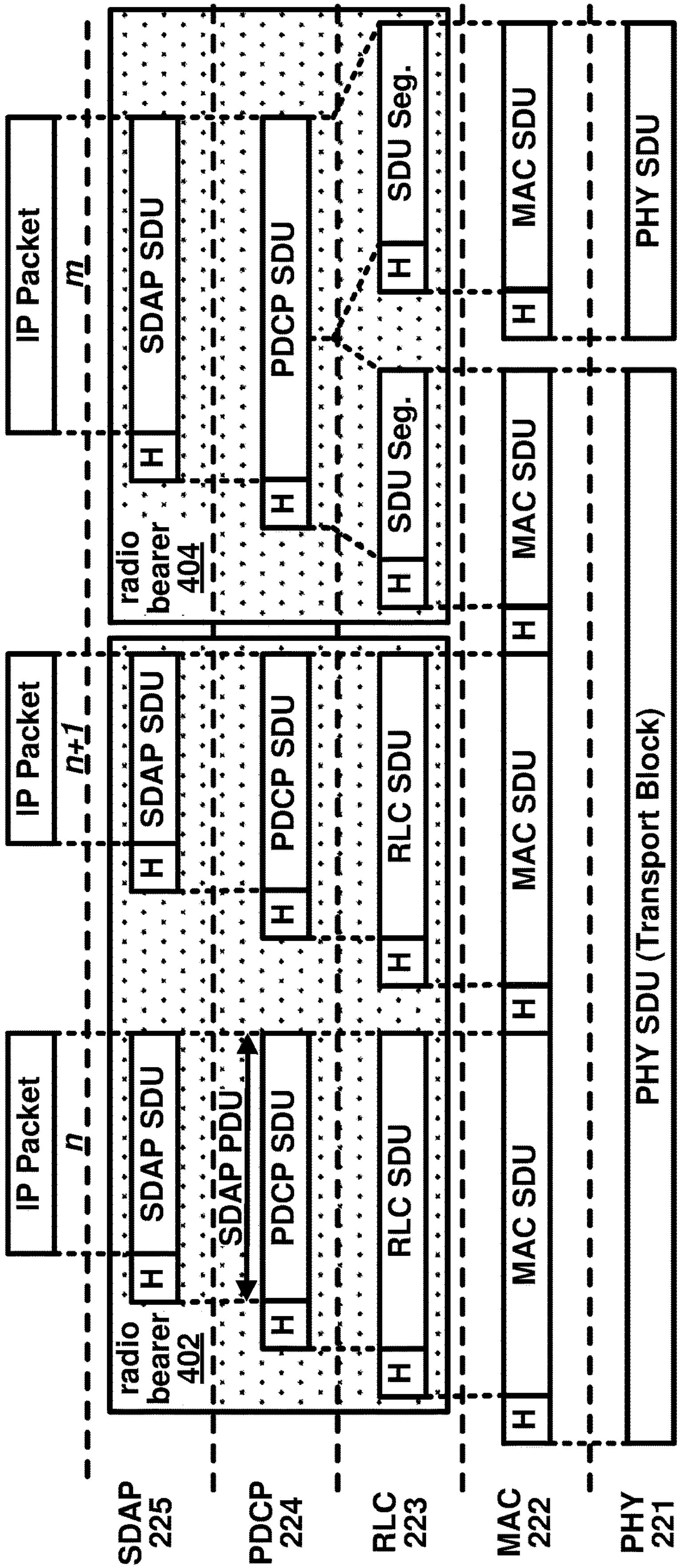
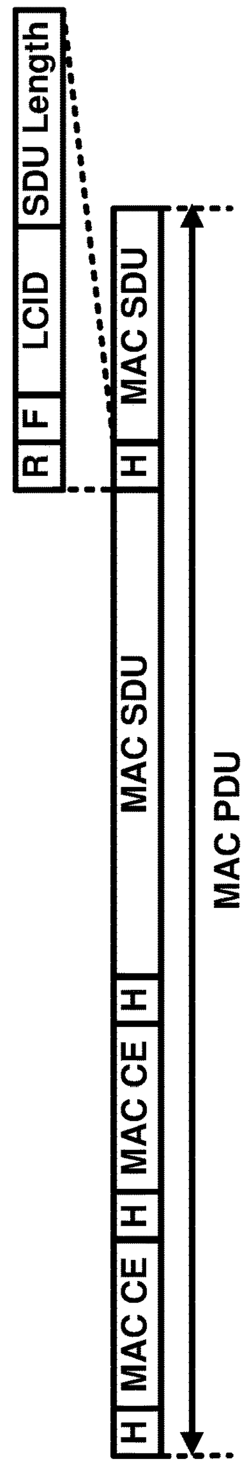

IP Packets
QoS Flows
SDAP 215/225
QoS Flow Handling
Radio Bearers
PDCP 214/224
Header Comp., Ciphering
Header Comp., Ciphering
Reordering, Retransmission
Reordering, Retransmission
RLC Channels
RLC 213/223
Segmentation, ARQ
Segmentation, ARQ
Logical Channels
MAC 212/222
Multiplexing
HARQ
Transport Channel
PHY 211/221
Coding, Resource Mapping

FIG. 3



SDAP 225
PDCP 224
RLC 223
MAC 222
PHY 221
IP Packet n
IP Packet n+1
IP Packet m
radio bearer 402
radio bearer 404
H
SDAP SDU
SDAP PDU
PDCP SDU
RLC SDU
SDU Seg.
MAC SDU
PHY SDU (Transport Block)
PHY SDU

FIG. 4A



R
F
LCID
SDU Length
H
MAC CE
MAC SDU
MAC PDU

FIG. 4B

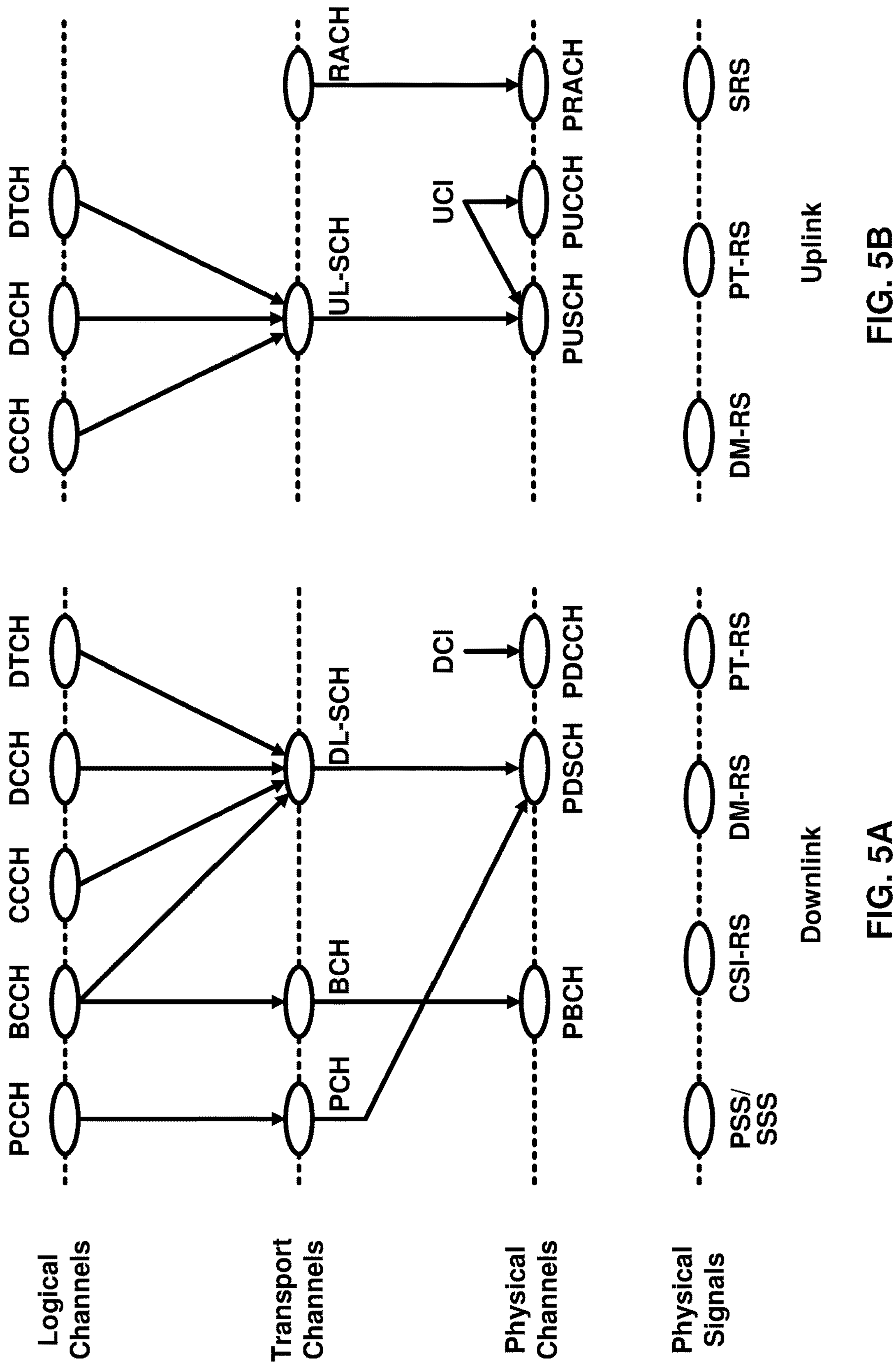

Logical Channels
Transport Channels
Physical Channels
Physical Signals
PCCH
BCCH
CCCH
DCCH
DTCH
PCH
BCH
DL-SCH
DCI
PBCH
PDSCH
PDCCH
PSS/SSS
CSI-RS
DM-RS
PT-RS
Downlink
CCCH
DCCH
DTCH
UL-SCH
RACH
UCI
PUSCH
PUCCH
PRACH
DM-RS
PT-RS
SRS
Uplink

FIG. 5A

FIG. 5B

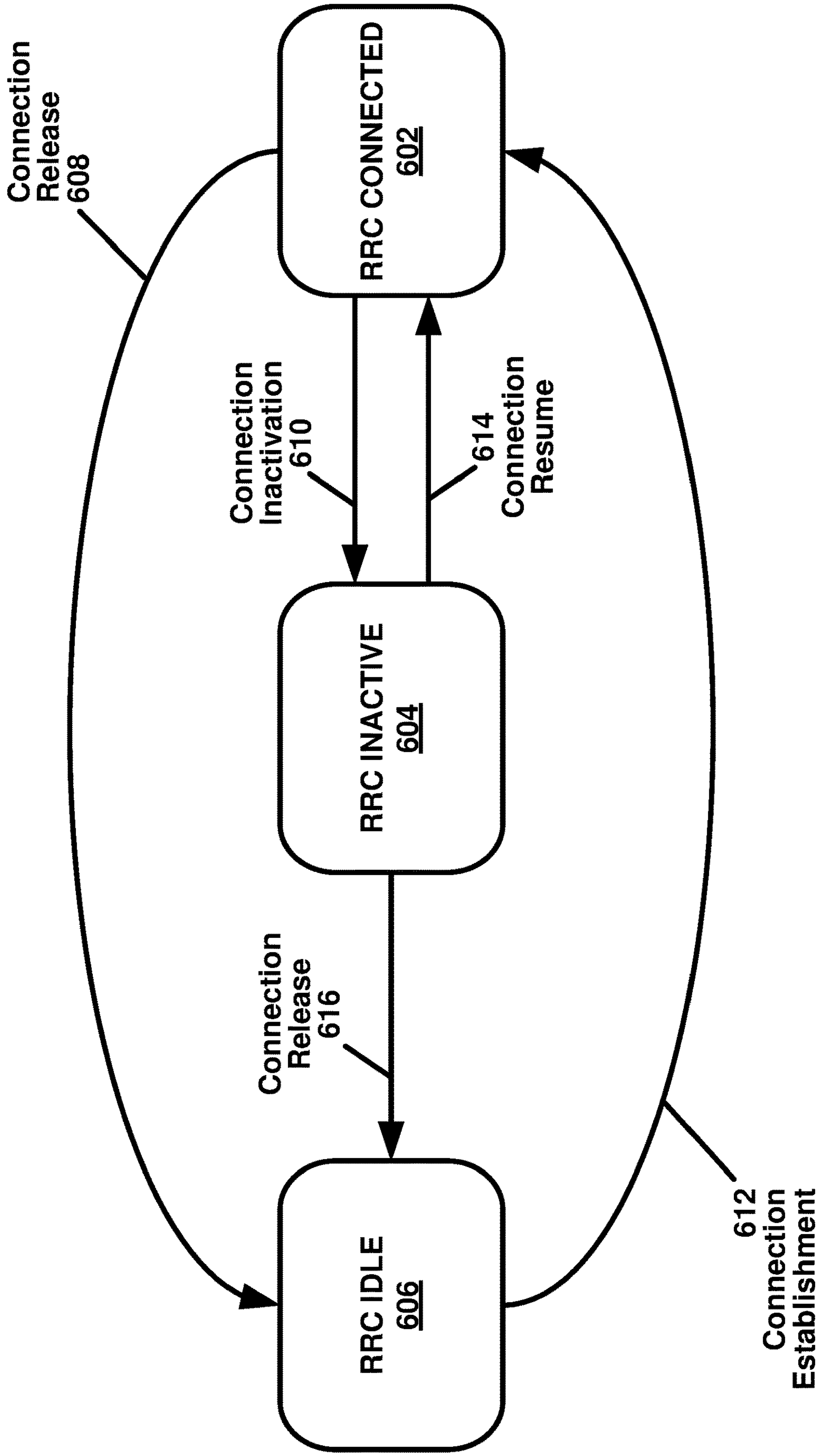

RRC CONNECTED
602
RRC INACTIVE
604
RRC IDLE
606
Connection Release 608
Connection Inactivation 610
612 Connection Establishment
614 Connection Resume
Connection Release 616

FIG. 6

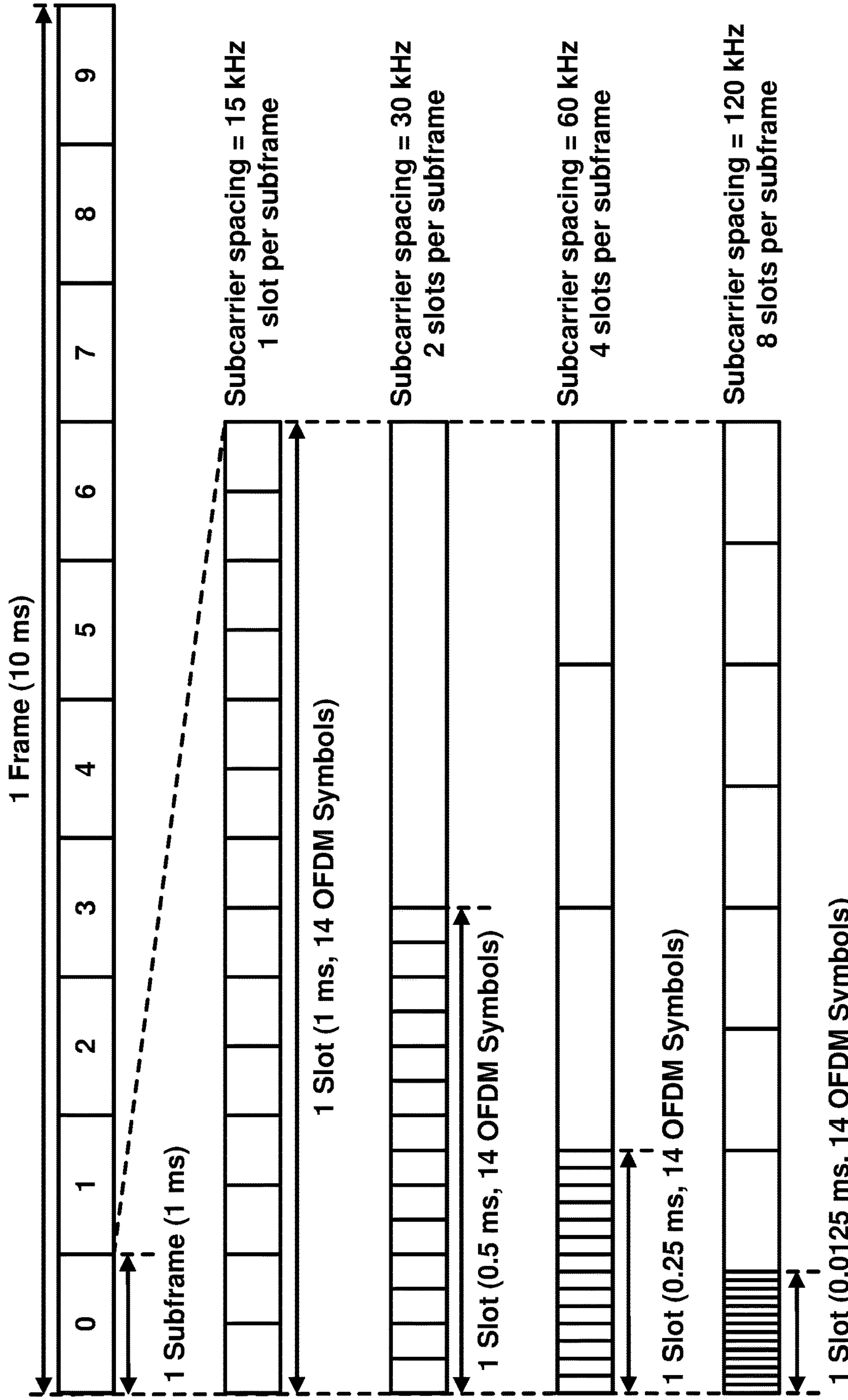

1 Frame (10 ms)
0
1
2
3
4
5
6
7
8
9
1 Subframe (1 ms)
Subcarrier spacing = 15 kHz
1 slot per subframe
1 Slot (1 ms, 14 OFDM Symbols)
Subcarrier spacing = 30 kHz
2 slots per subframe
1 Slot (0.5 ms, 14 OFDM Symbols)
Subcarrier spacing = 60 kHz
4 slots per subframe
1 Slot (0.25 ms, 14 OFDM Symbols)
Subcarrier spacing = 120 kHz
8 slots per subframe
1 Slot (0.0125 ms, 14 OFDM Symbols)

FIG. 7

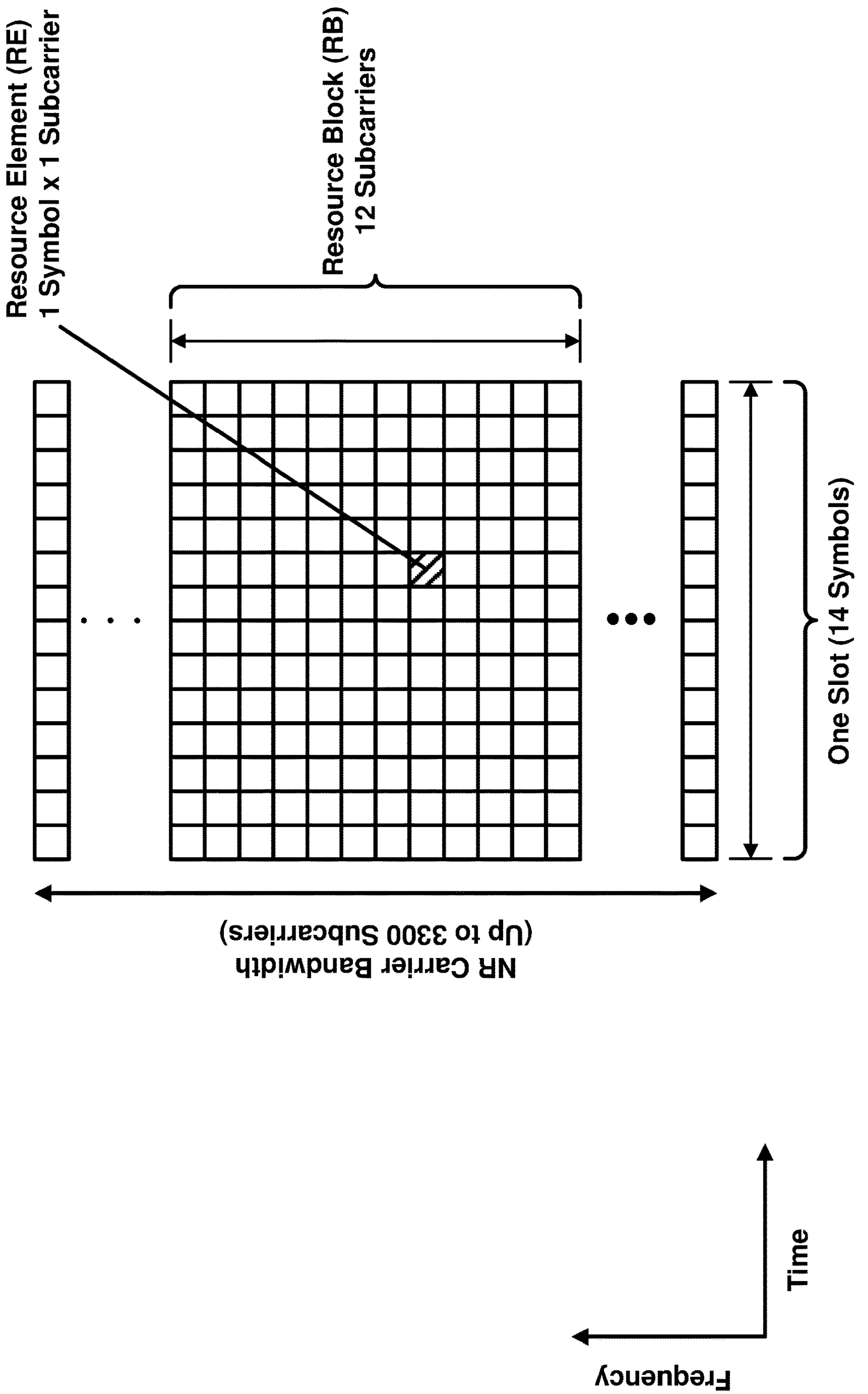

Resource Element (RE)
1 Symbol x 1 Subcarrier
Resource Block (RB)
12 Subcarriers
One Slot (14 Symbols)
NR Carrier Bandwidth
(Up to 3300 Subcarriers)
Time
Frequency

FIG. 8

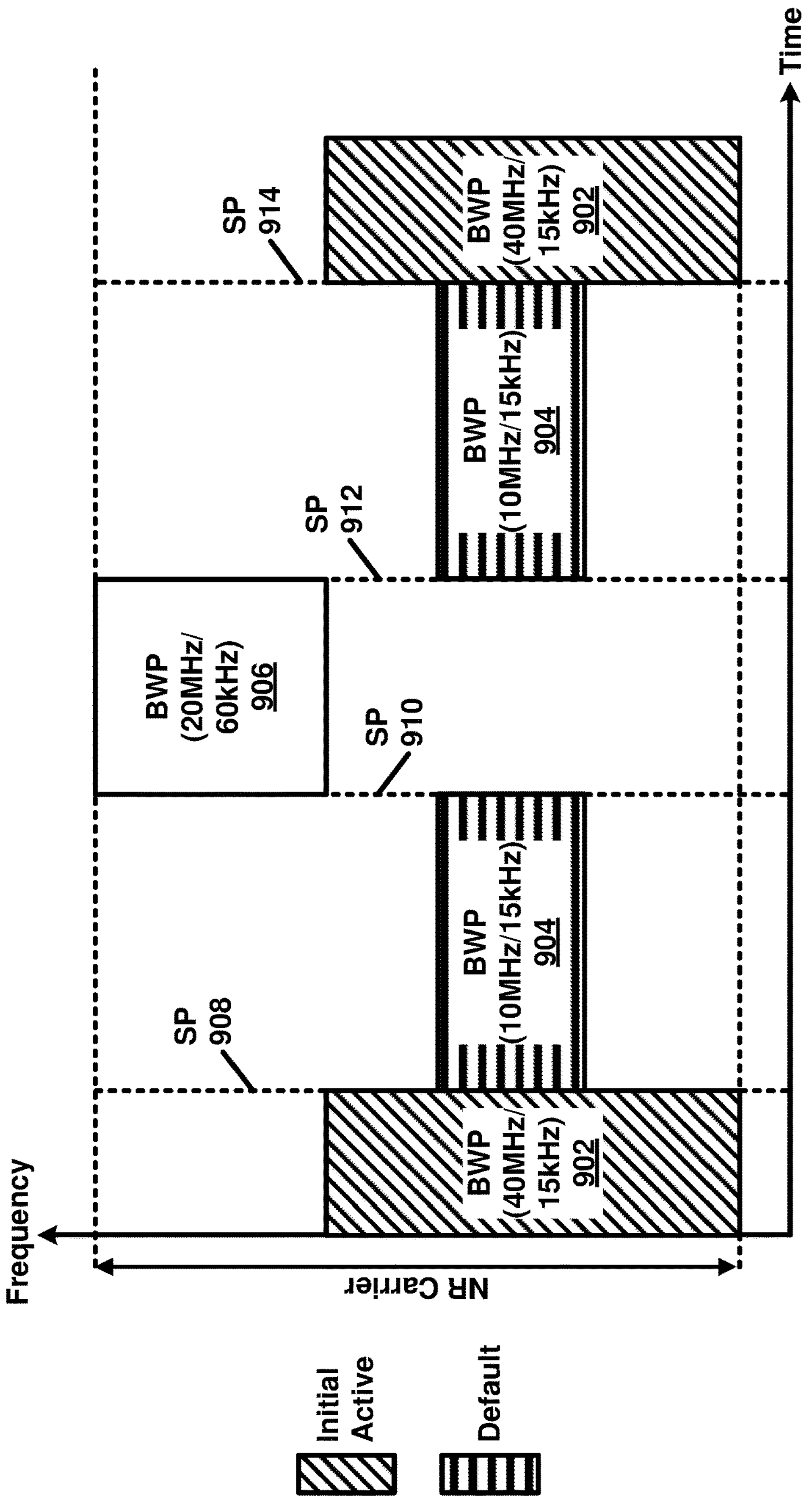

Time
Frequency
NR Carrier
SP 908
SP 910
SP 912
SP 914
BWP (40MHz/15kHz) 902
BWP (10MHz/15kHz) 904
BWP (20MHz/60kHz) 906
BWP (10MHz/15kHz) 904
BWP (40MHz/15kHz) 902
Initial Active
Default

FIG. 9

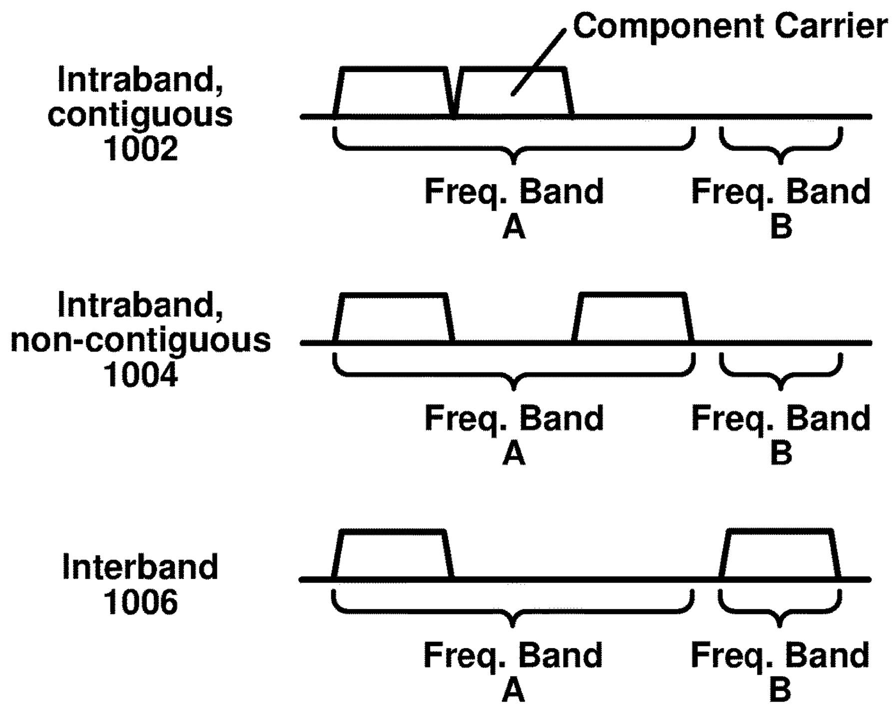


FIG. 10A

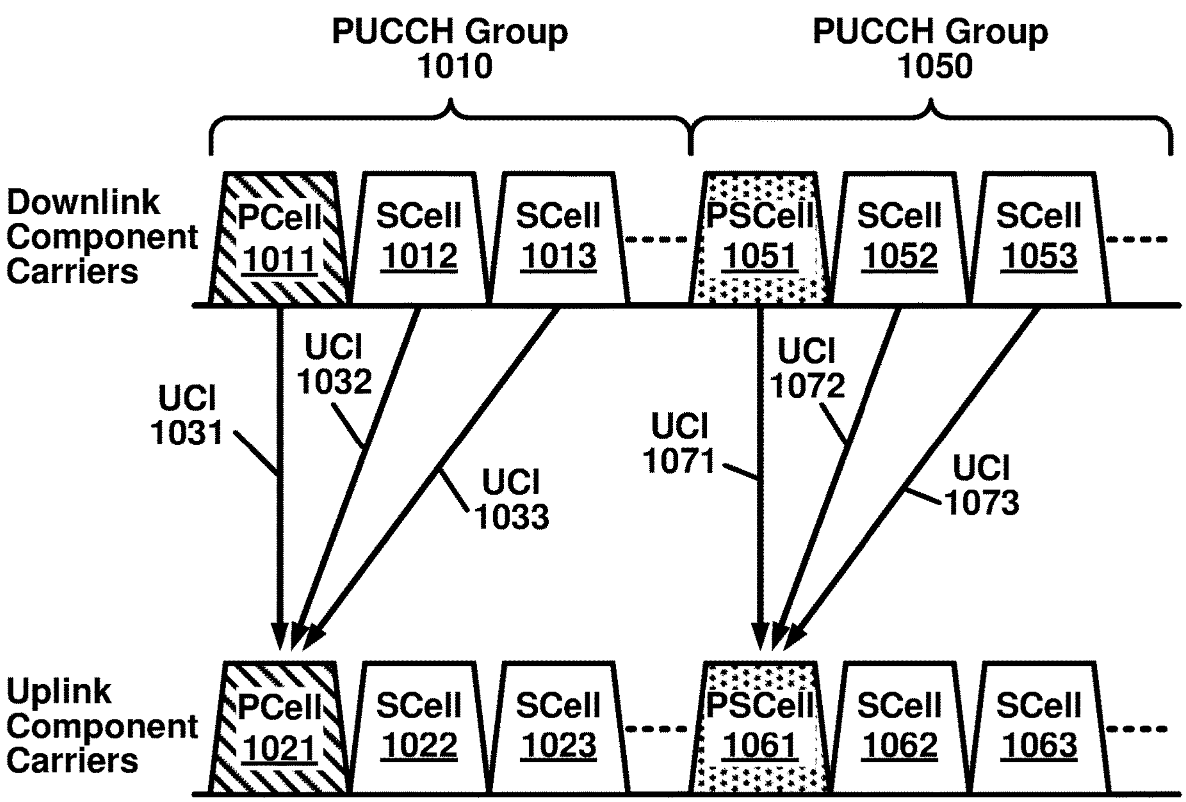


FIG. 10B

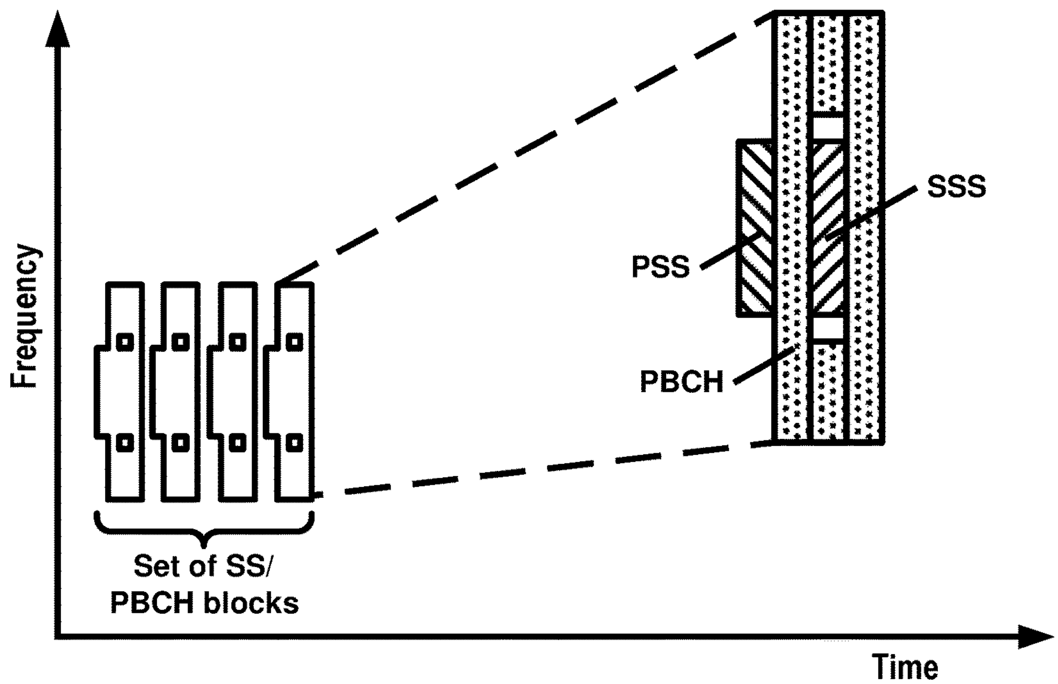


FIG. 11A

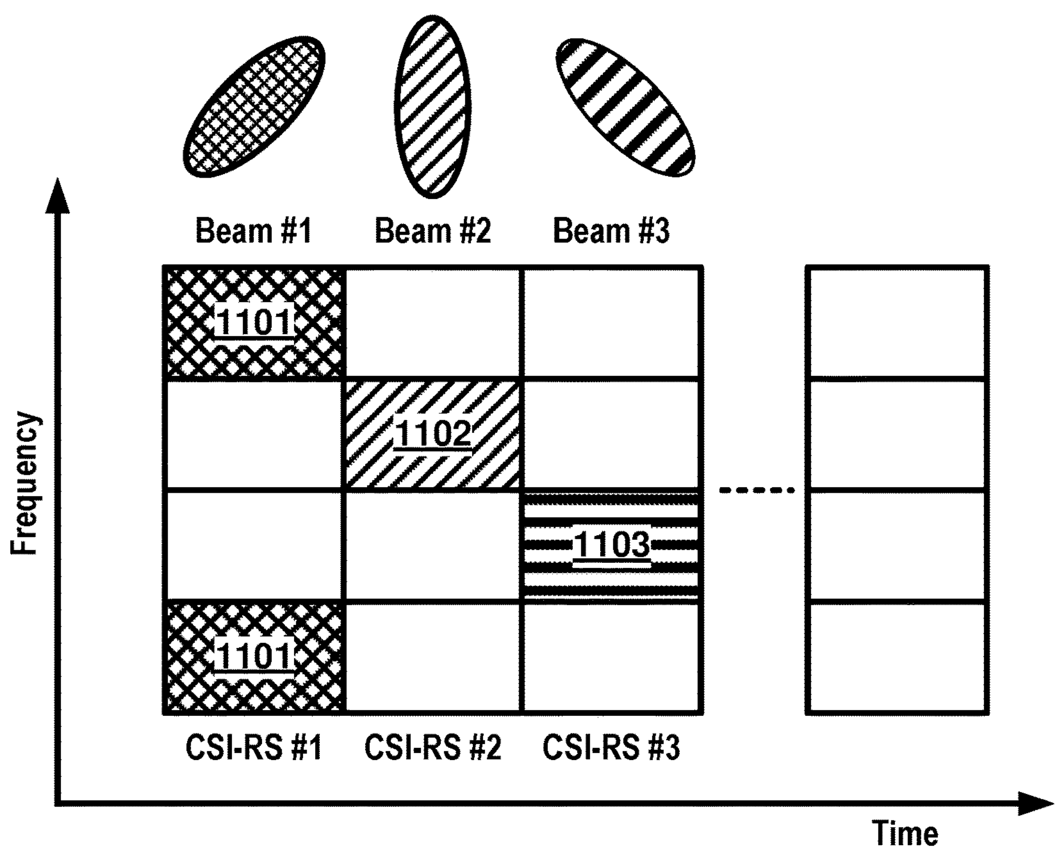


FIG. 11B

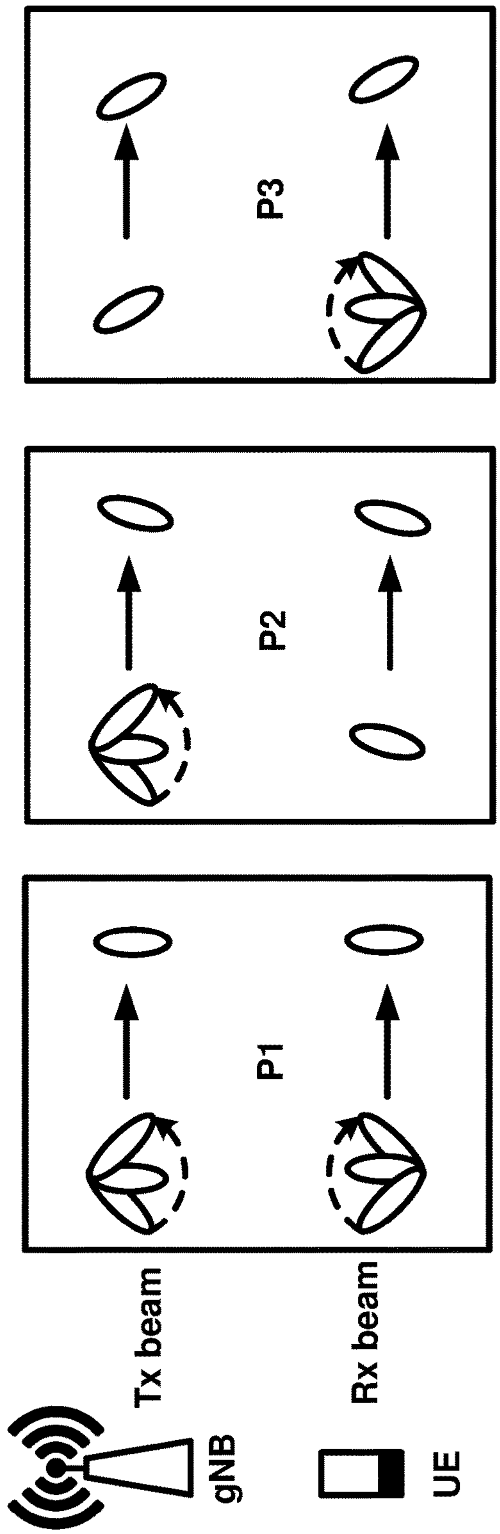


FIG. 12A

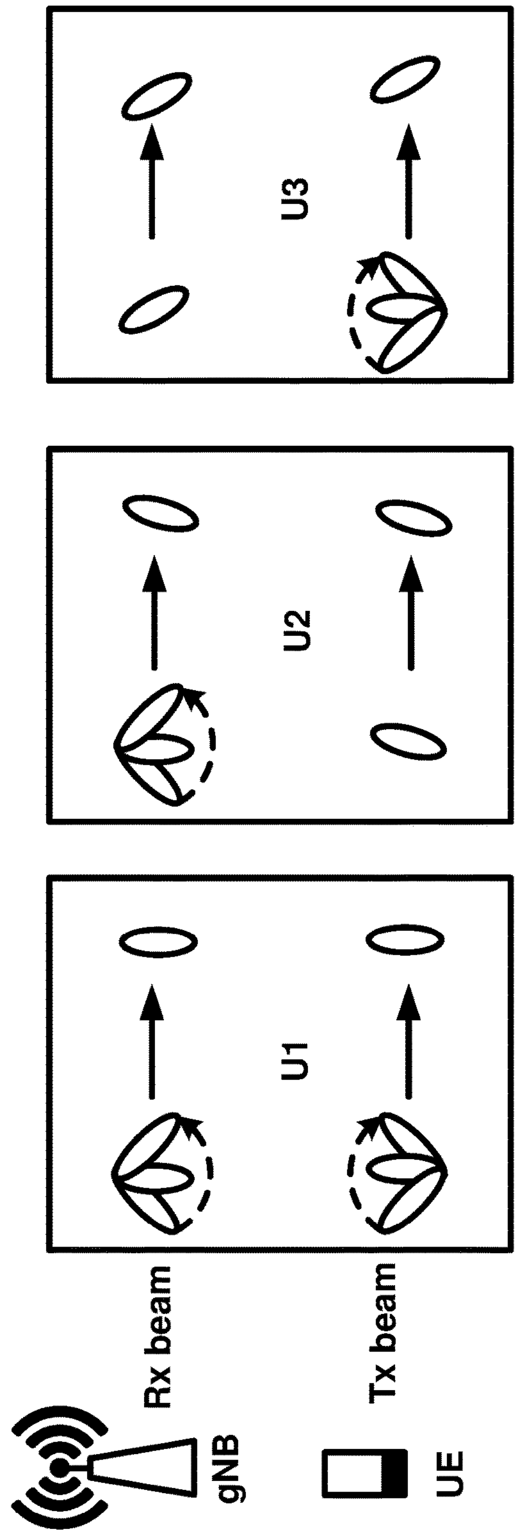


FIG. 12B

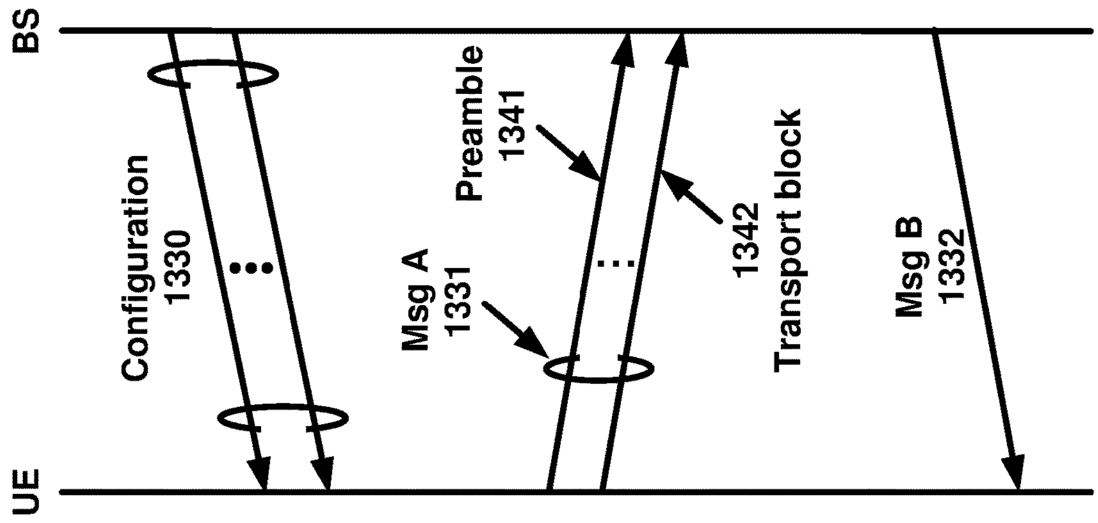


FIG. 13C

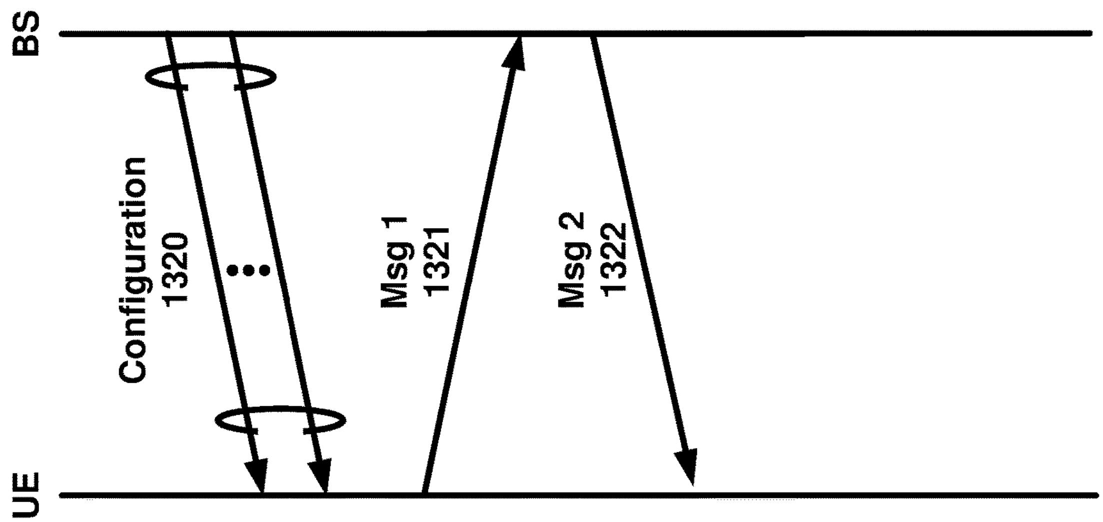


FIG. 13B

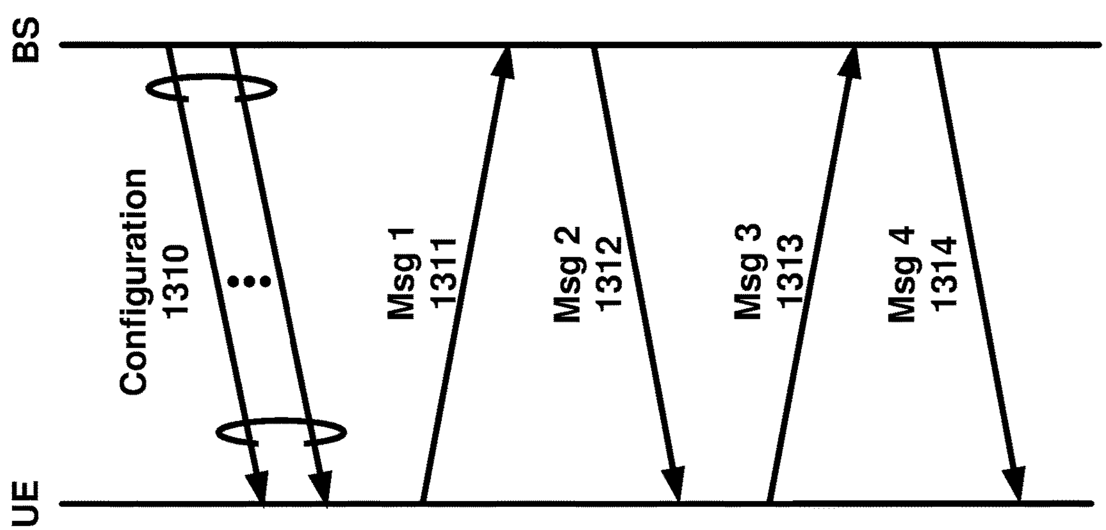


FIG. 13A

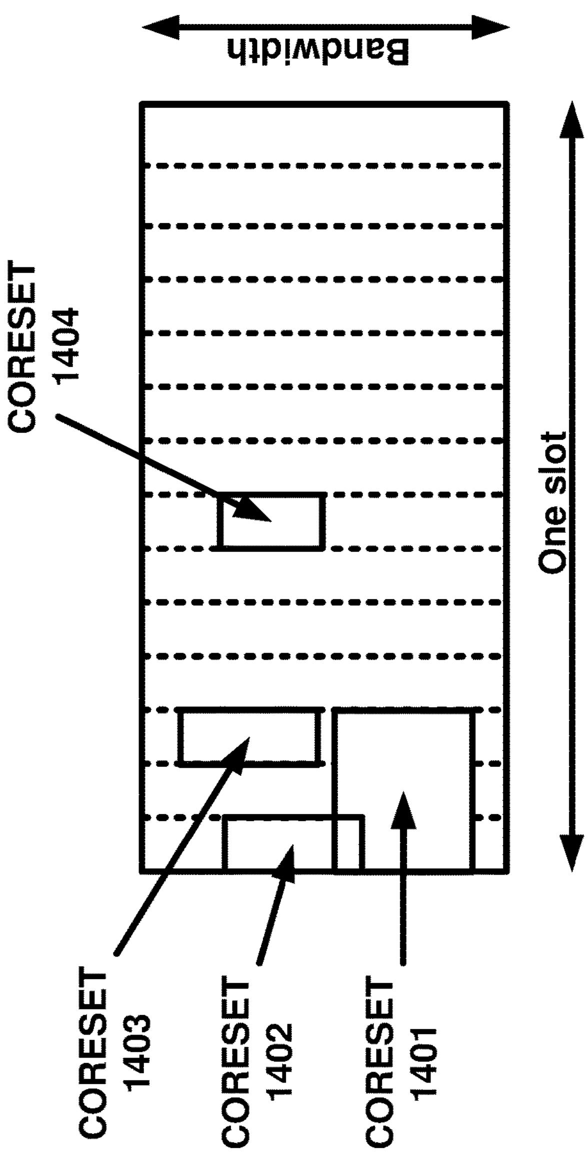


FIG. 14A

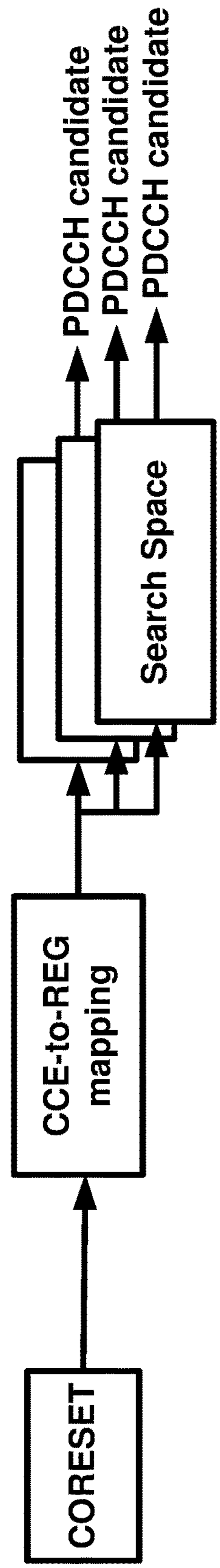


FIG. 14B

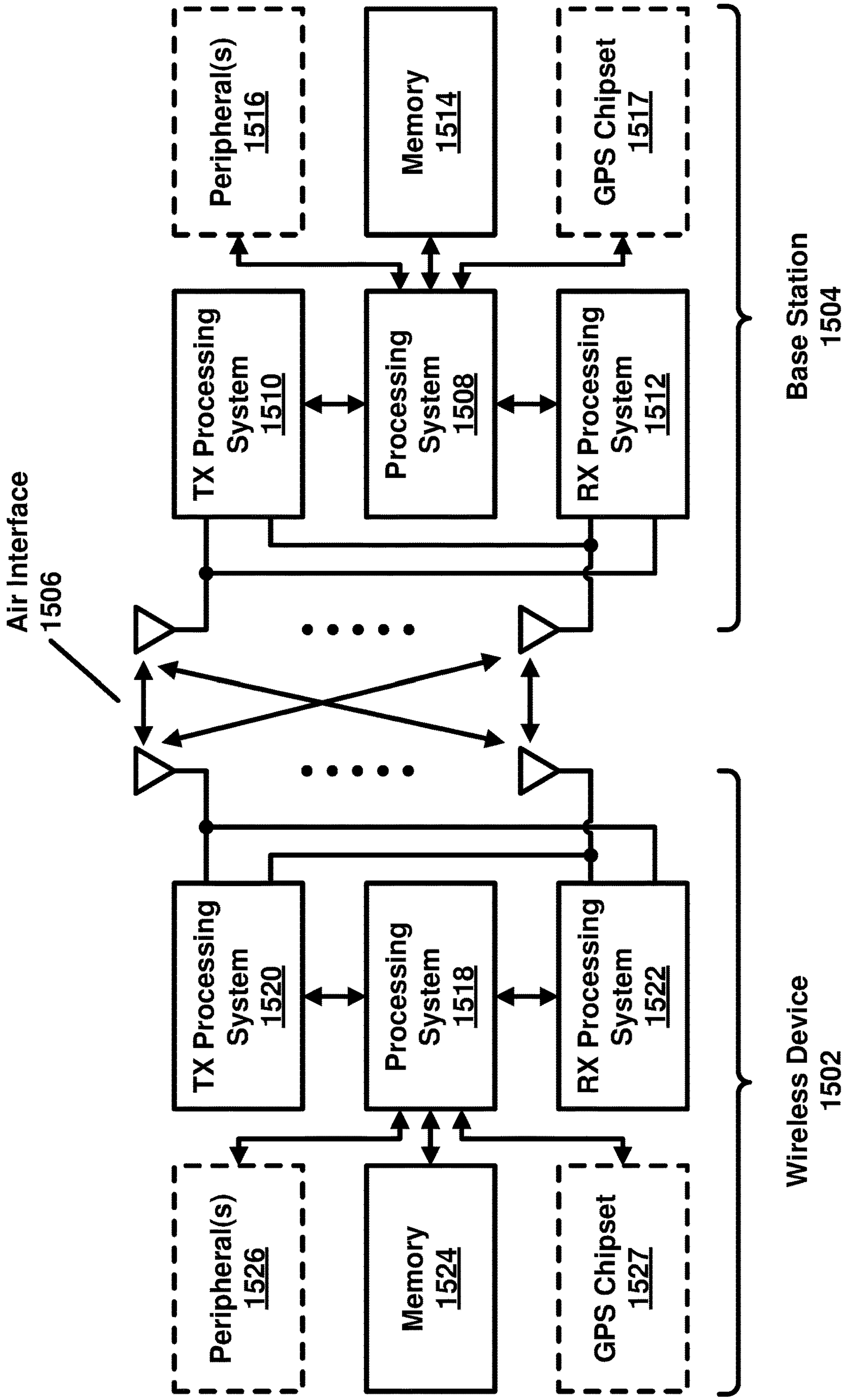

Peripheral(s)
1516
Memory
1514
GPS Chipset
1517
TX Processing System
1510
Processing System
1508
RX Processing System
1512
Base Station
1504
Air Interface
1506
TX Processing System
1520
Processing System
1518
RX Processing System
1522
Wireless Device
1502
Peripheral(s)
1526
Memory
1524
GPS Chipset
1527

FIG. 15

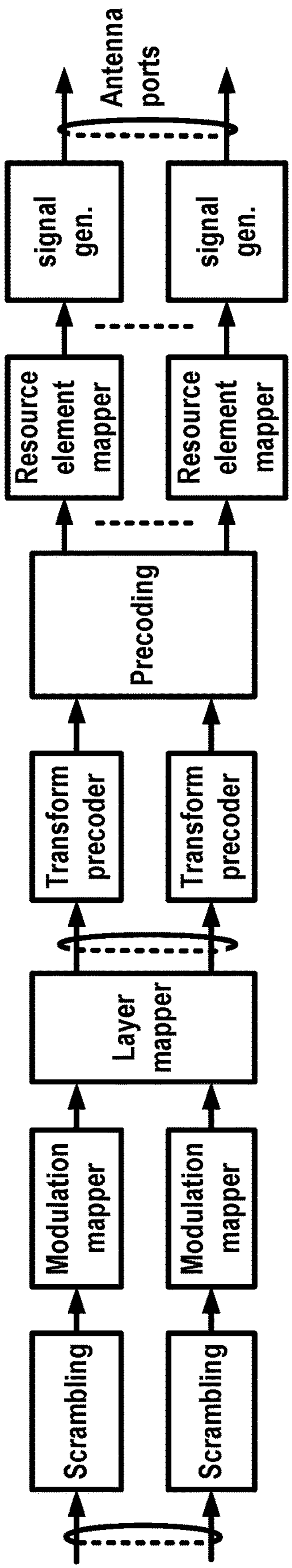


FIG. 16A

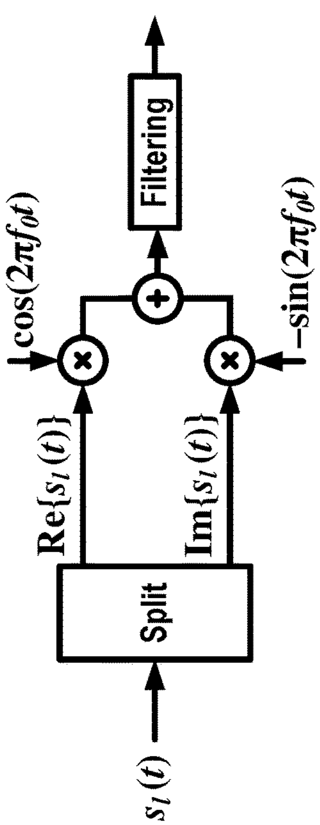


FIG. 16B

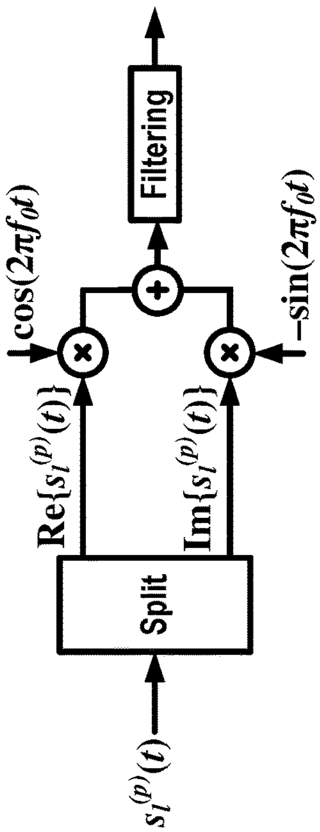


FIG. 16D

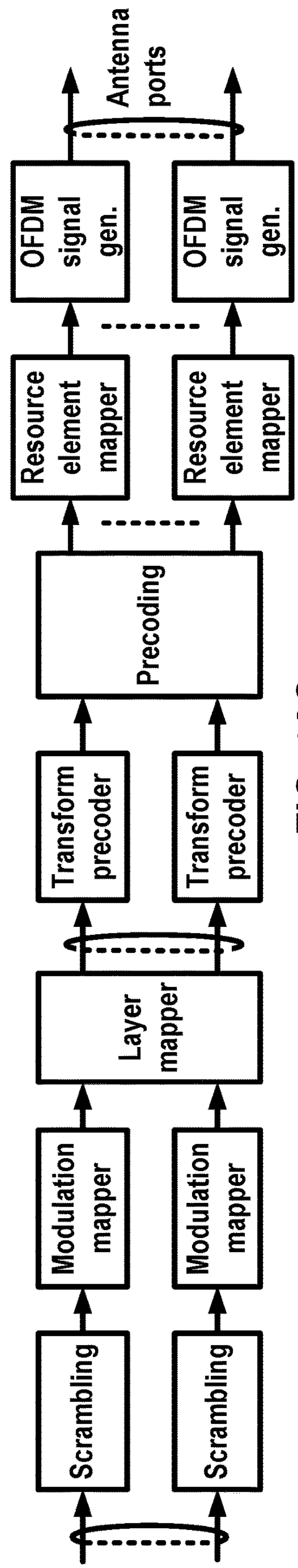


FIG. 16C

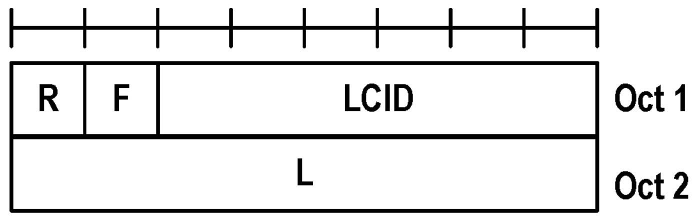


FIG. 17A

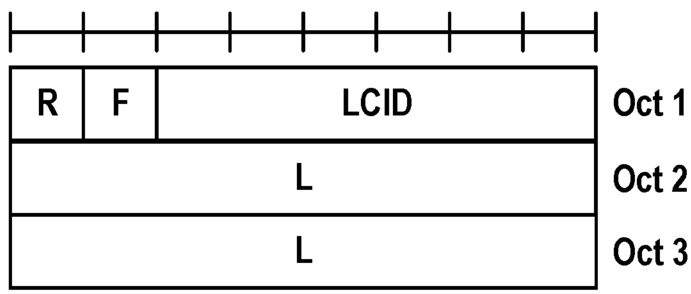


FIG. 17B

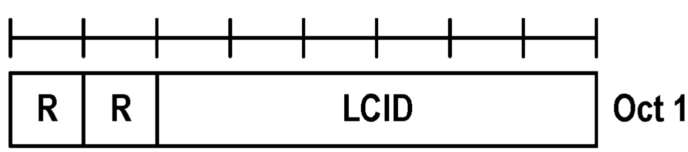


FIG. 17C

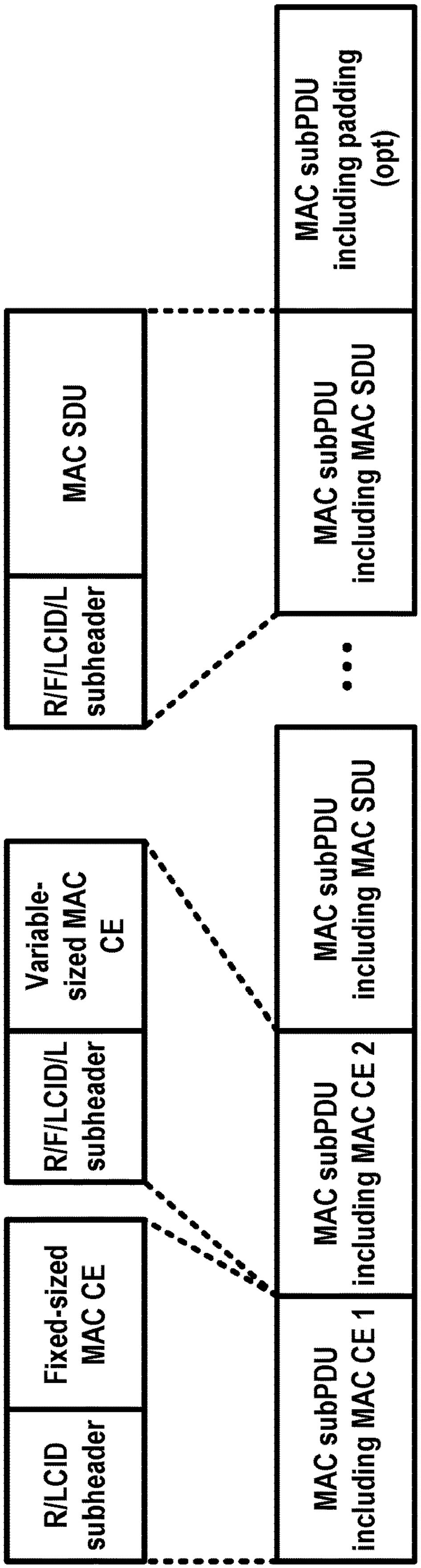


FIG. 18A

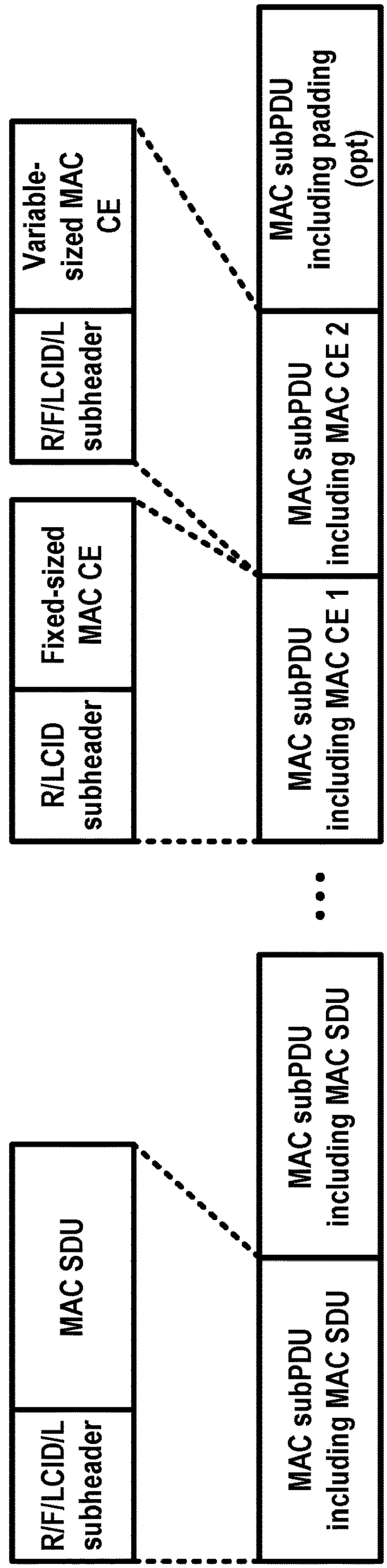


FIG. 18B

Index	LCID values
000000	CCCH
000001-100000	Identity of a logical channel
100001-101111	Reserved
110000	SP ZP CSI-RS Resource Set Act./Deact.
110001	PUCCH spatial relation Act./Deact.
110010	SP SRS Act./Deact.
110011	SP CSI reporting on PUCCH Act./Deact.
110100	TCI State Indication for UE-specific PDCCH
110101	TCI State Indication for UE-specific PDSCH
110110	Aperiodic CSI Trigger State Subselection
110111	SP CSI-RS/CSI-IM Resource Set Act./Deact.
111000	Duplication Activation/deactivation
111001	SCell activation/deactivation (4 Octet)
111010	SCell activation/deactivation (1 Octet)
111011	Long DRX Command
111100	DRX Command
111101	Timing Advance Command
111110	UE Contention Resolution Identity
111111	Padding

FIG. 19

Index	LCID values
000000	CCCH
000001-100000	Identity of a logical channel
100001-110110	Reserved
110111	Configured Grant Confirmation
111000	Multiple Entry PHR
111001	Single Entry PHR
111010	C-RNTI
111011	Short Truncated BSR
111100	Long Truncated BSR
111101	Short BSR
111110	Long BSR
111111	Padding

FIG. 20

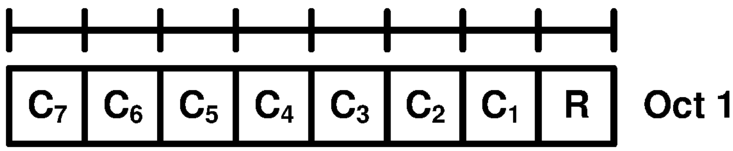


FIG. 21A

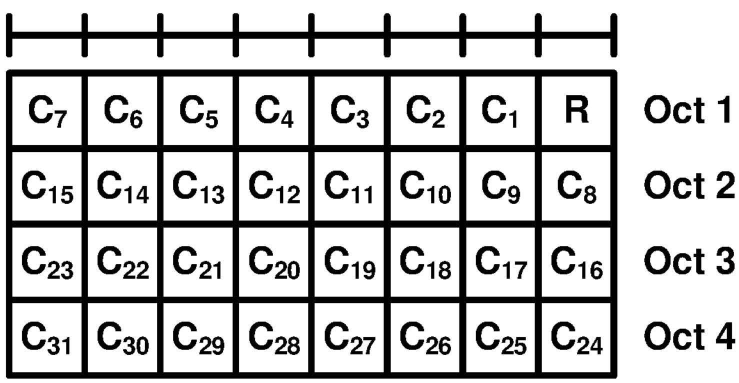


FIG. 21B

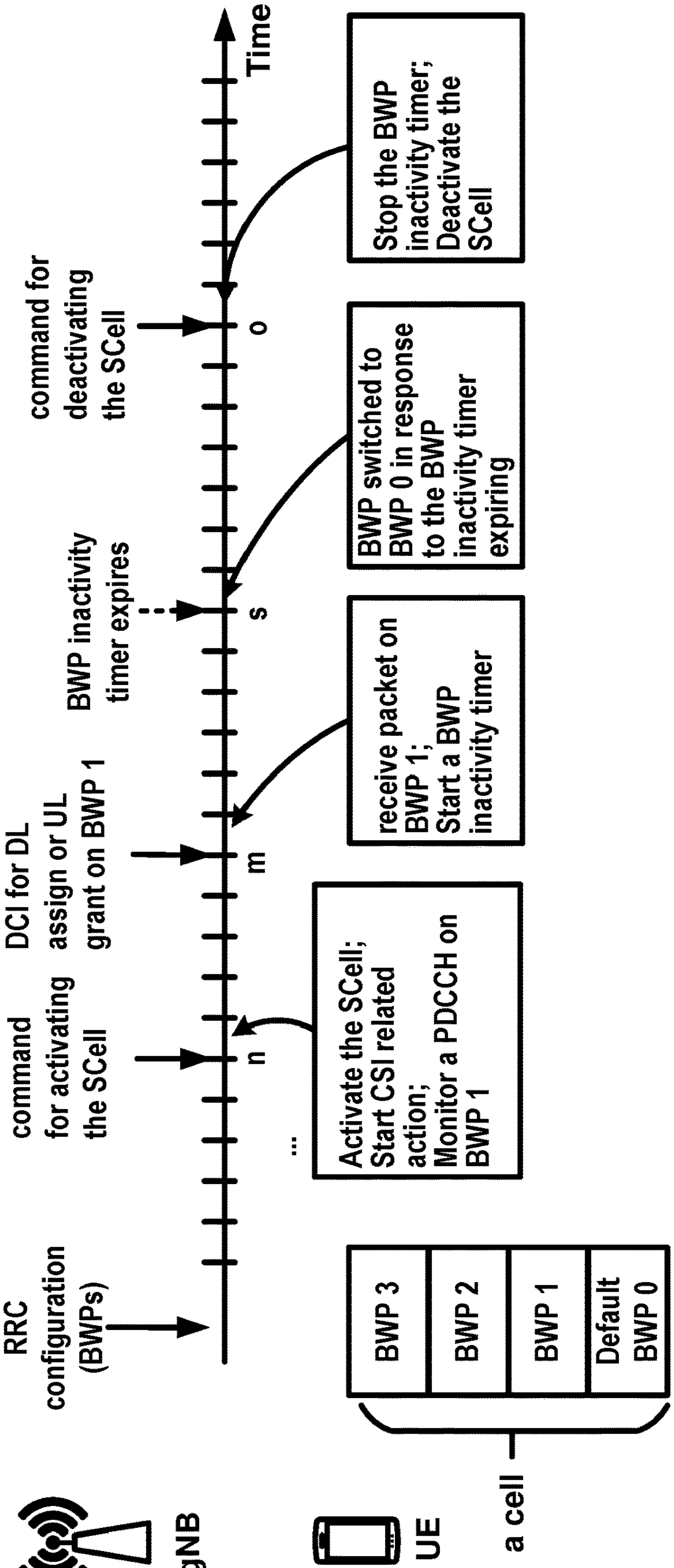

gNB
UE
a cell
BWP 3
BWP 2
BWP 1
Default BWP 0
RRC configuration (BWPs)
command for activating the SCell
DCI for DL assign or UL grant on BWP 1
BWP inactivity timer expires
command for deactivating the SCell
Time
...
n
m
s
o
Activate the SCell; Start CSI related action; Monitor a PDCCH on BWP 1
receive packet on BWP 1; Start a BWP inactivity timer
BWP switched to BWP 0 in response to the BWP inactivity timer expiring
Stop the BWP inactivity timer; Deactivate the SCell

FIG. 22

– *SearchSpace*

The IE *SearchSpace* defines how/where to search for PDCCH candidates. Each search space is associated with one *ControlResourceSet*. For a scheduled cell in the case of cross carrier scheduling, except for *nrofCandidates*, all the optional fields are absent.

***SearchSpace* information element**

```
SearchSpace ::=                SEQUENCE {
  searchSpaceId         SearchSpaceId,
  controlResourceSetId   ControlResourceSetId   OPTIONAL,   -- Cond SetupOnly
  monitoringSlotPeriodicityAndOffset     CHOICE {
    sl1                          NULL,
    sl2                          INTEGER (0..1),          ... }           OPTIONAL,   -- Cond Setup
  duration      INTEGER (2..2559)          OPTIONAL,   -- Need R
  monitoringSymbolsWithinSlot   BIT STRING (SIZE (14)) OPTIONAL, -- Cond Setup
  nrofCandidates              SEQUENCE {
    aggregationLevel1       ENUMERATED {n0, n1, n2, n3, n4, n5, n6, n8},
          ...}                OPTIONAL,   -- Cond Setup
  searchSpaceType       CHOICE {
    common                       SEQUENCE {         dci-Format0-0-AndFormat1-0     SEQUENCE {
         ...} OPTIONAL,   -- Need R
         ...},
    ue-Specific     SEQUENCE {         dci-Formats   ENUMERATED {formats0-0-And-1-0, formats0-1-And-1-1},
        ...}
  }  OPTIONAL    -- Cond Setup
}
```

searchSpaceId

Identity of the search space. SearchSpaceId = 0 identifies the *searchSpaceZero* configured via PBCH (MIB) or *ServingCellConfigCommon* and may hence not be used in the *SearchSpace* IE. The searchSpaceId is unique among the BWPs of a Serving Cell. In case of cross carrier scheduling, search spaces with the same *searchSpaceId* in scheduled cell and scheduling cell are linked to each other. The UE applies the search space for the scheduled cell only if the DL BWPs in which the linked search spaces are configured in scheduling cell and scheduled cell are both active.

FIG. 23

– *ControlResourceSet*

The IE *ControlResourceSet* is used to configure a time/frequency CORESET in which to search for DCI.

```
ControlResourceSet ::=          SEQUENCE {
   controlResourceSetId          ControlResourceSetId,
   frequencyDomainResources      BIT STRING (SIZE (45)),
   duration                      INTEGER (1..maxCoReSetDuration),
   cce-REG-MappingType           CHOICE { interleaved          SEQUENCE {...}, nonInterleaved    NULL},
   precoderGranularity           ENUMERATED {sameAsREG-bundle, allContiguousRBs},
   tci-StatesPDCCH-ToAddList     SEQUENCE(SIZE (1..maxNrofTCI-StatesPDCCH)) OF TCI-StateId OPTIONAL
   tci-StatesPDCCH-ToReleaseList SEQUENCE(SIZE (1..maxNrofTCI-StatesPDCCH)) OF TCI-StateId OPTIONAL
   tci-PresentInDCI              ENUMERATED {enabled}                OPTIONAL, -- Need S
   pdcch-DMRS-ScramblingID       INTEGER (0..65535)                  OPTIONAL, -- Need S
   ...}
```

controlResourceSetId

Values 1..*maxNrofControlResourceSets-1* identify CORESETs configured by dedicated signalling or in *SIB1*.

duration

Contiguous time duration of the CORESET in number of symbols .

frequencyDomainResources

Frequency domain resources for the CORESET. Each bit corresponds a group of 6 RBs, with grouping starting from the first RB group in the BWP.

tci-PresentInDCI

This field indicates if TCI field is present or absent in DL-related DCI.

tci-StatesPDCCH-ToAddList

A subset of the TCI states defined in pdsch-Config included in the *BWP-DownlinkDedicated* corresponding to the serving cell and to the DL BWP to which the *ControlResourceSet* belong to.

FIG. 24

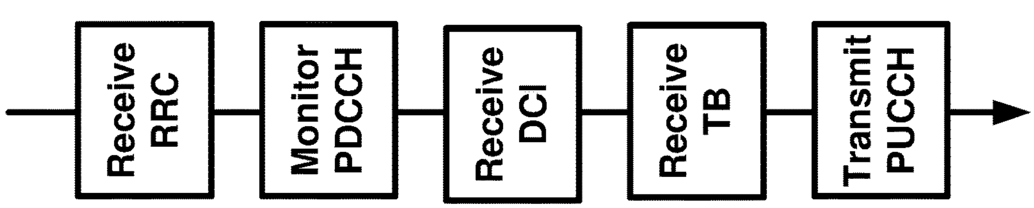


FIG. 25A

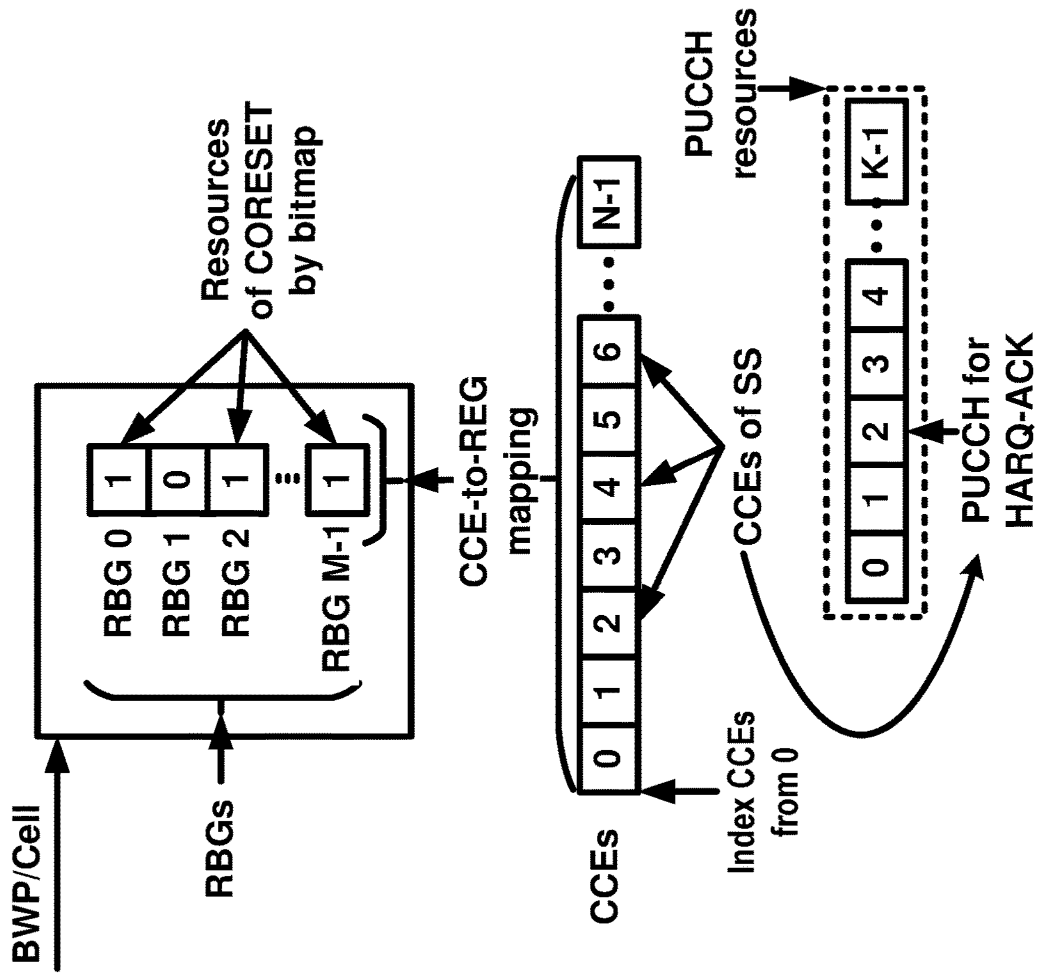


FIG. 25B

PUCCH resource indicator	PUCCH resource
'000'	1st PUCCH resource identified by PUCCH resource identifier obtained from the 1st value of PUCCH resource list
'001'	2nd PUCCH resource identified by PUCCH resource identifier obtained from the 2nd value of PUCCH resource list
'010'	3rd PUCCH resource identified by PUCCH resource identifier obtained from the 3rd value of PUCCH resource list
'011'	4th PUCCH resource identified by PUCCH resource identifier obtained from the 4th value of PUCCH resource list
'100'	5th PUCCH resource identified by PUCCH resource identifier obtained from the 5th value of PUCCH resource list
'101'	6th PUCCH resource identified by PUCCH resource identifier obtained from the 6th value of PUCCH resource list
'110'	7th PUCCH resource identified by PUCCH resource identifier obtained from the 7th value of PUCCH resource list
'111'	8th PUCCH resource identified by PUCCH resource identifier obtained from the 8th value of PUCCH resource list

FIG. 26

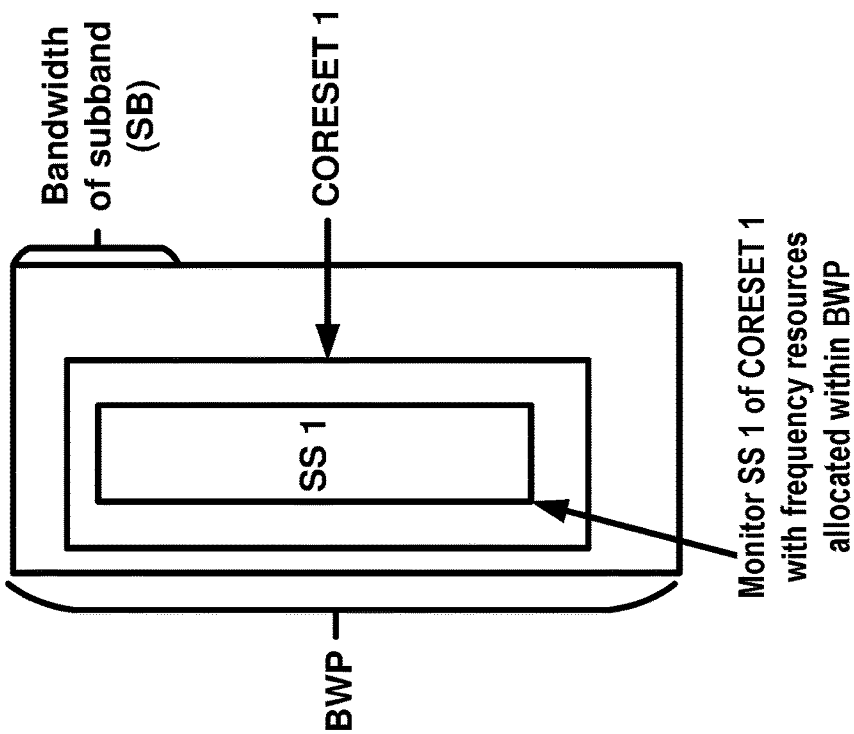


FIG. 27A

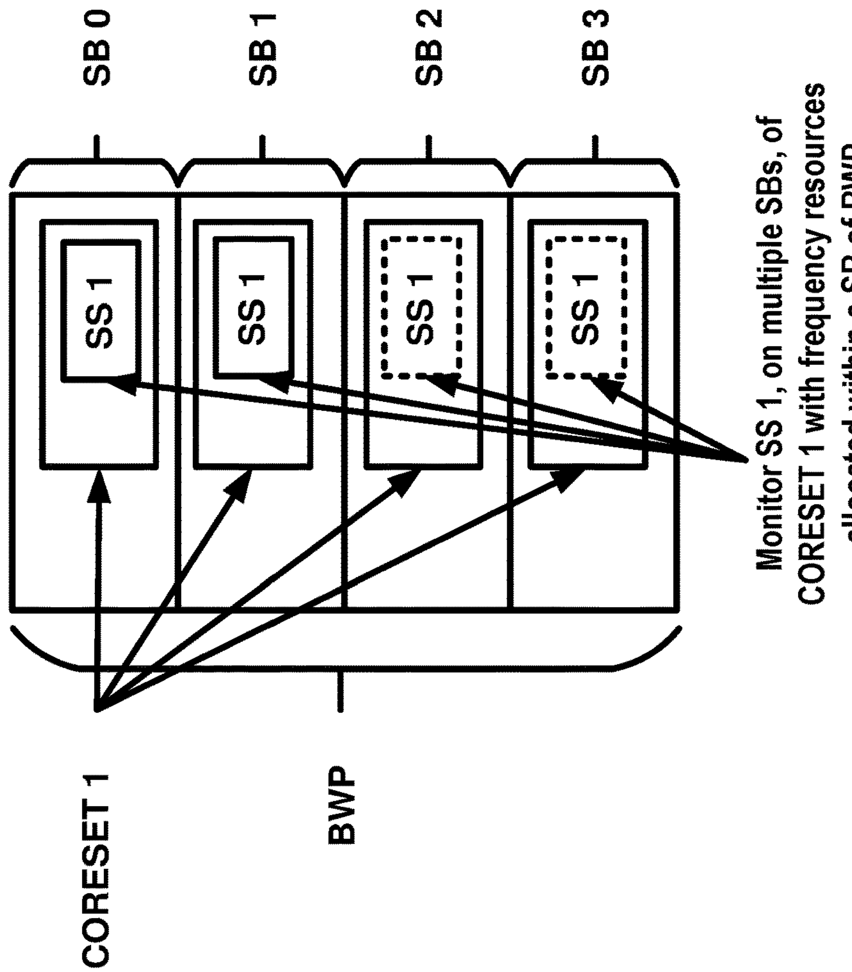
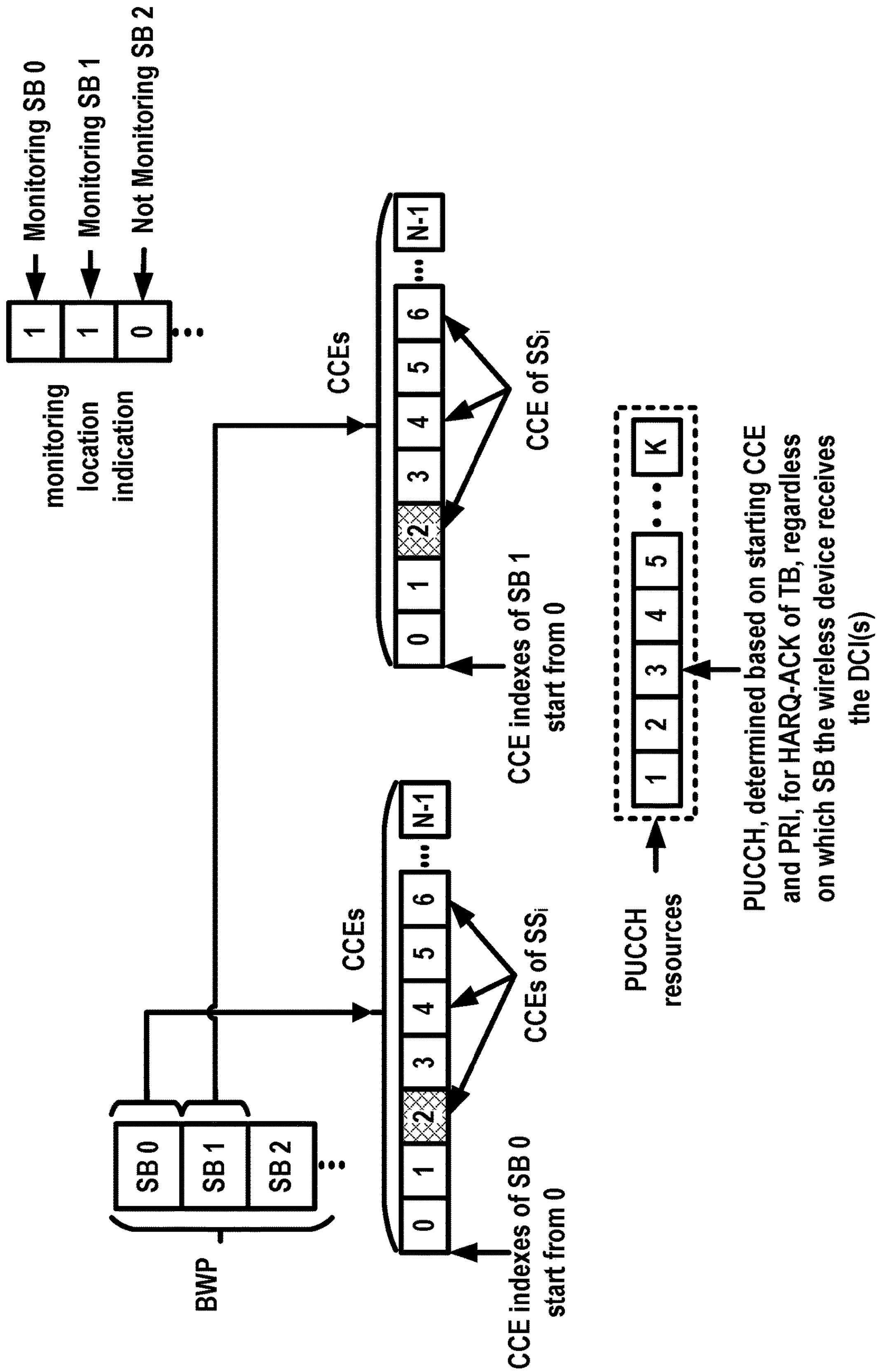
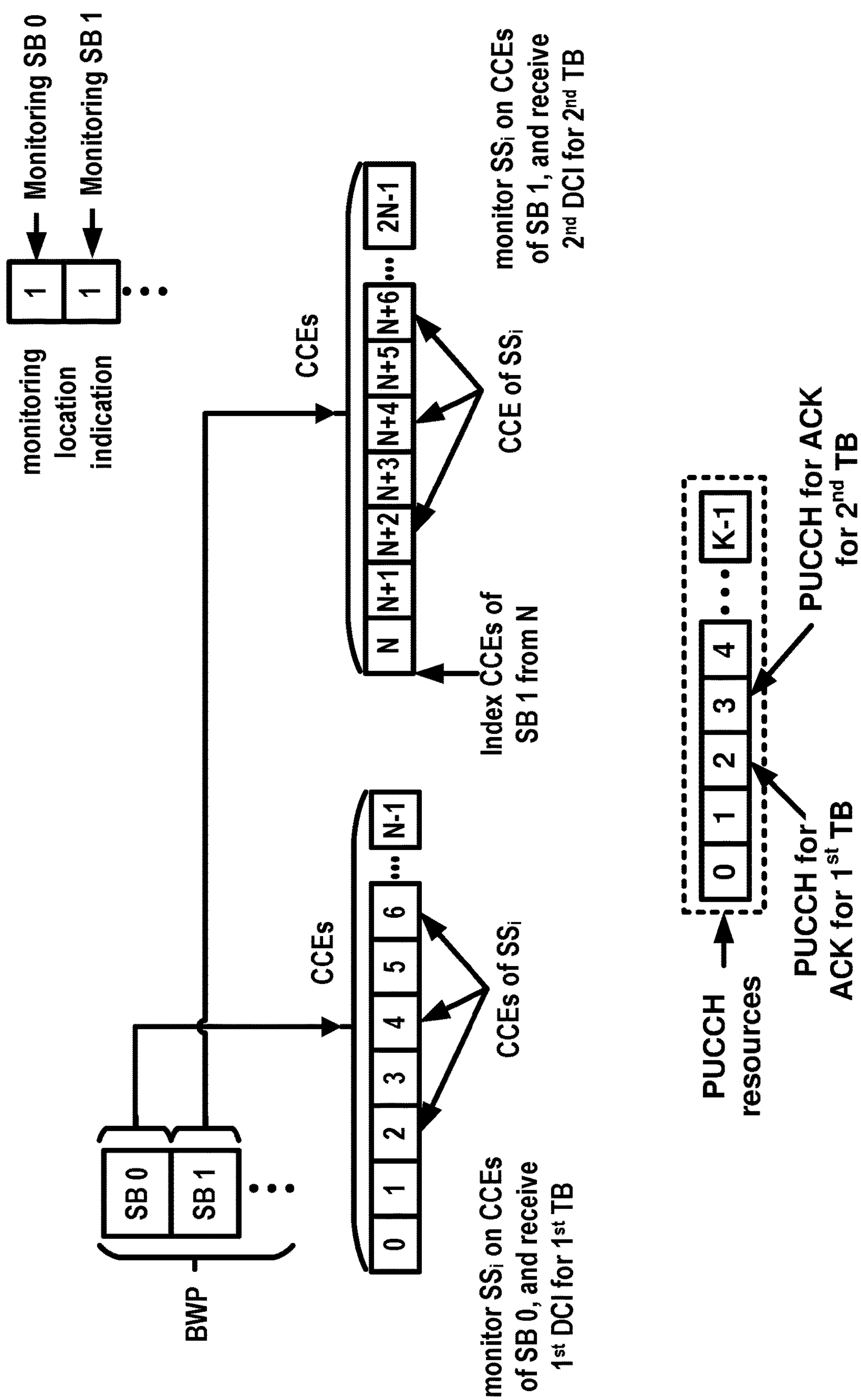


FIG. 27B



monitoring location indication
1
1
0
Monitoring SB 0
Monitoring SB 1
Not Monitoring SB 2
BWP
SB 0
SB 1
SB 2
CCEs
0
1
2
3
4
5
6
N-1
CCEs of SSi
CCE indexes of SB 0 start from 0
CCEs
0
1
2
3
4
5
6
N-1
CCE of SSi
CCE indexes of SB 1 start from 0
PUCCH resources
1
2
3
4
5
K
PUCCH, determined based on starting CCE and PRI, for HARQ-ACK of TB, regardless on which SB the wireless device receives the DCI(s)

FIG. 28



BWP
SB 0
SB 1
monitoring location indication
Monitoring SB 0
Monitoring SB 1
CCEs
CCEs of SSi
monitor SSi on CCEs of SB 0, and receive 1st DCI for 1st TB
CCEs
CCE of SSi
Index CCEs of SB 1 from N
monitor SSi on CCEs of SB 1, and receive 2nd DCI for 2nd TB
PUCCH resources
PUCCH for ACK for 1st TB
PUCCH for ACK for 2nd TB

FIG. 29

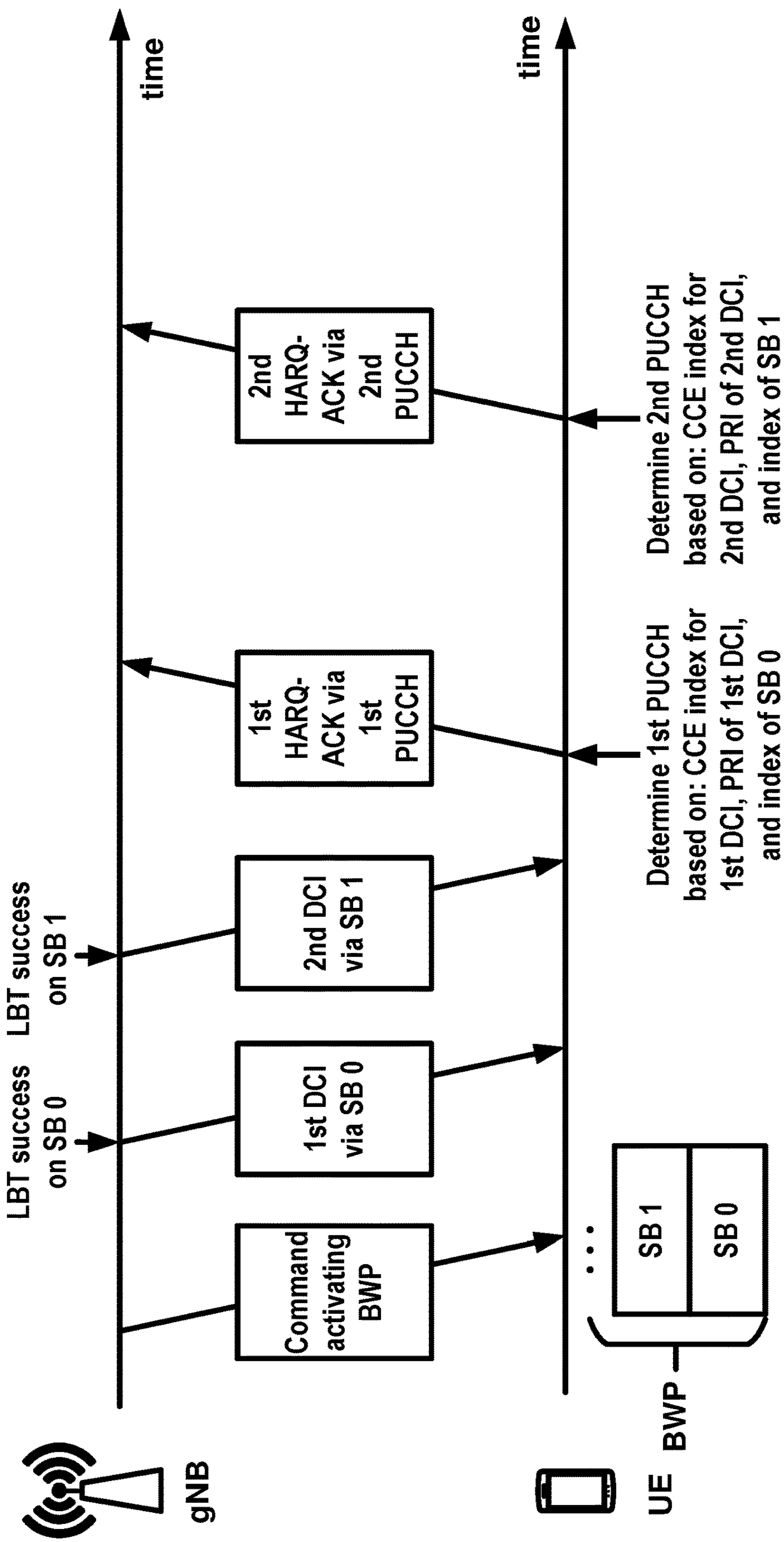

gNB
UE
time
time
LBT success on SB 0
LBT success on SB 1
Command activating BWP
1st DCI via SB 0
2nd DCI via SB 1
1st HARQ-ACK via 1st PUCCH
2nd HARQ-ACK via 2nd PUCCH
Determine 1st PUCCH based on: CCE index for 1st DCI, PRI of 1st DCI, and index of SB 0
Determine 2nd PUCCH based on: CCE index for 2nd DCI, PRI of 2nd DCI, and index of SB 1
BWP
SB 1
SB 0
• • •

FIG. 30

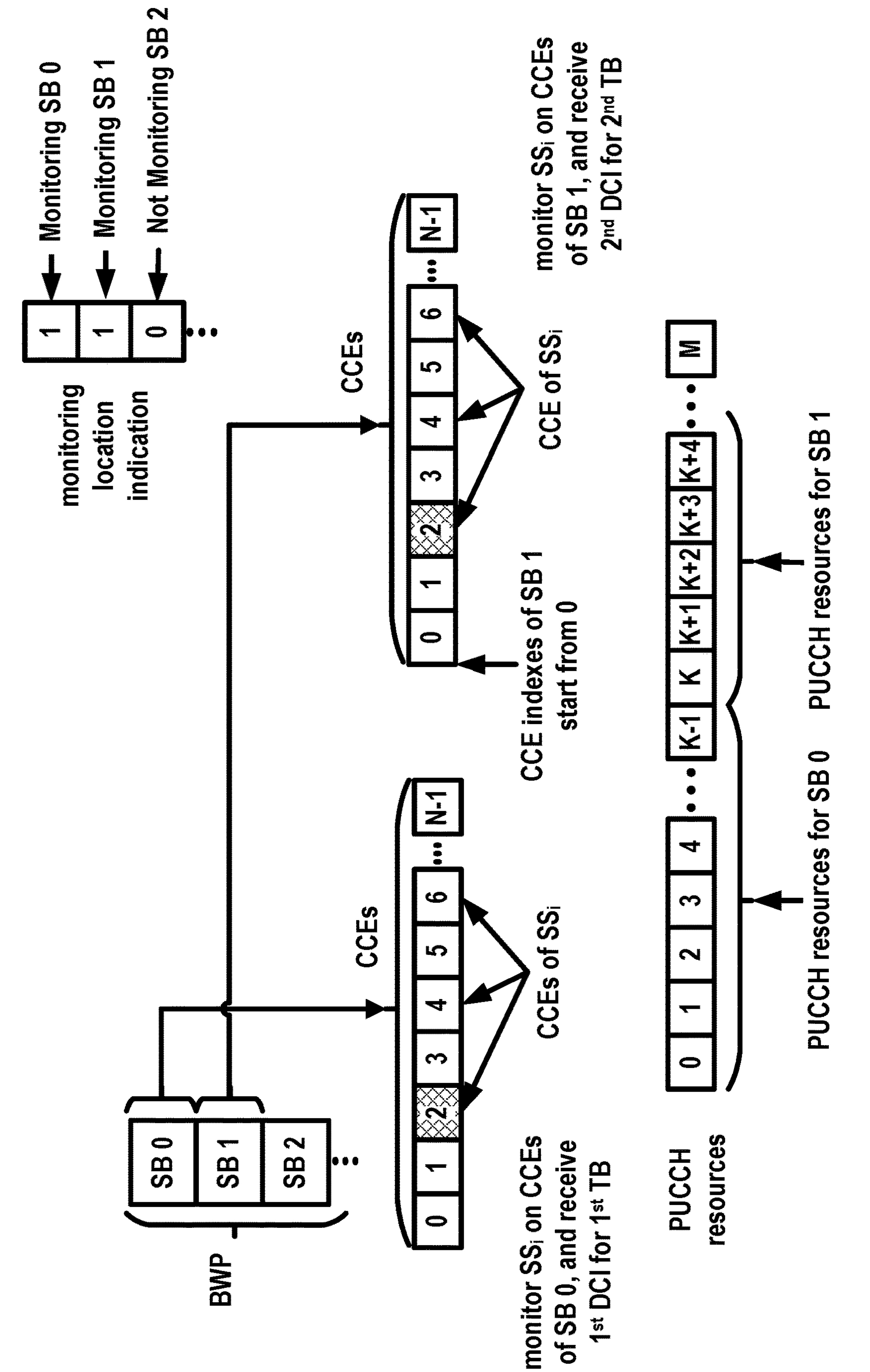

Monitoring SB 0
Monitoring SB 1
Not Monitoring SB 2
1
1
0
monitoring location indication
BWP
SB 0
SB 1
SB 2
CCEs
0
1
2
3
4
5
6
N-1
CCEs of SS$_i$
monitor SS$_i$ on CCEs of SB 0, and receive 1st DCI for 1st TB
CCEs
0
1
2
3
4
5
6
N-1
CCE of SS$_i$
CCE indexes of SB 1 start from 0
monitor SS$_i$ on CCEs of SB 1, and receive 2nd DCI for 2nd TB
PUCCH resources
0
1
2
3
4
K-1
K
K+1
K+2
K+3
K+4
M
PUCCH resources for SB 0
PUCCH resources for SB 1

FIG. 31

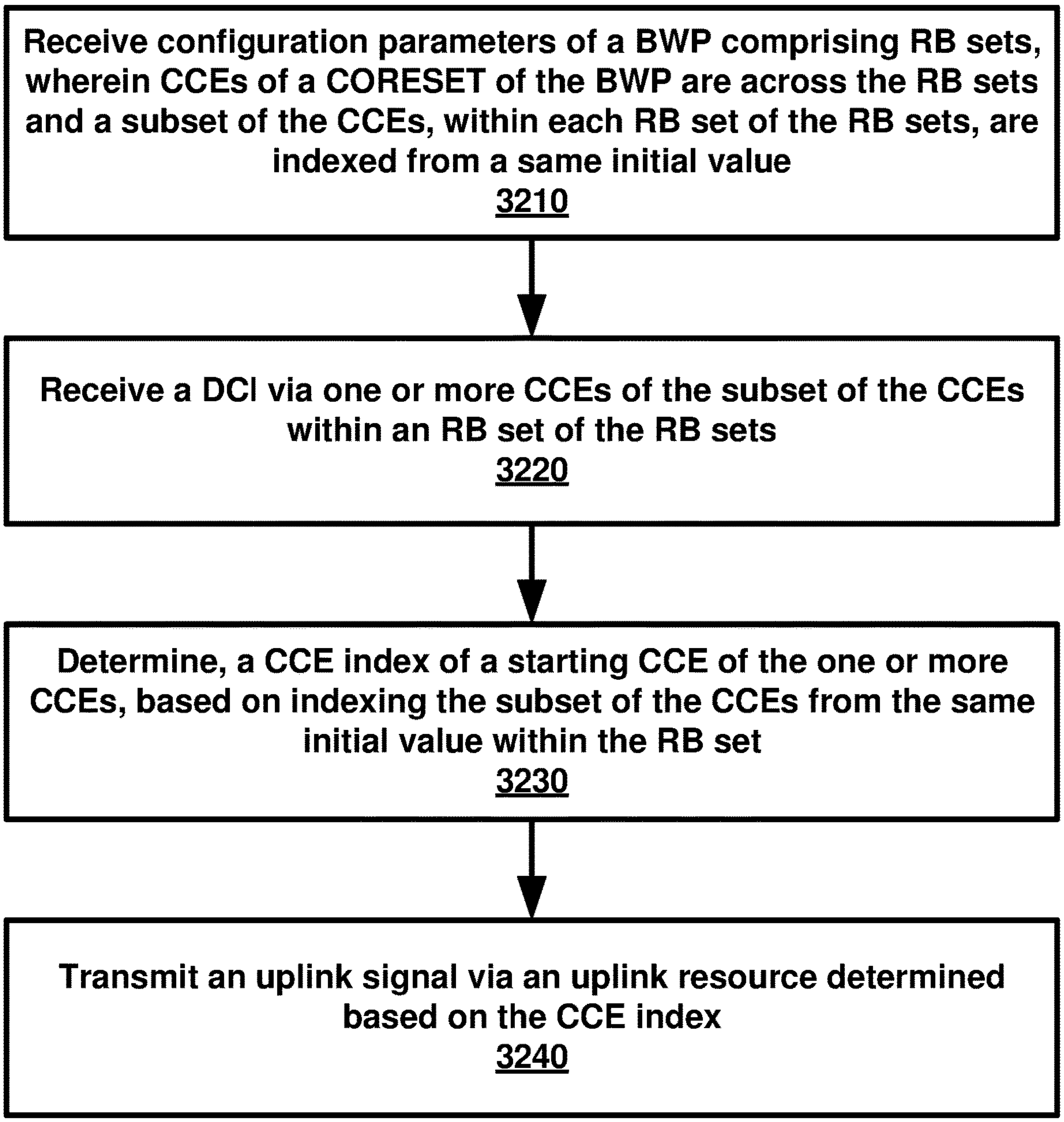

Receive configuration parameters of a BWP comprising RB sets, wherein CCEs of a CORESET of the BWP are across the RB sets and a subset of the CCEs, within each RB set of the RB sets, are indexed from a same initial value
3210
Receive a DCI via one or more CCEs of the subset of the CCEs within an RB set of the RB sets
3220
Determine, a CCE index of a starting CCE of the one or more CCEs, based on indexing the subset of the CCEs from the same initial value within the RB set
3230
Transmit an uplink signal via an uplink resource determined based on the CCE index
3240

FIG. 32

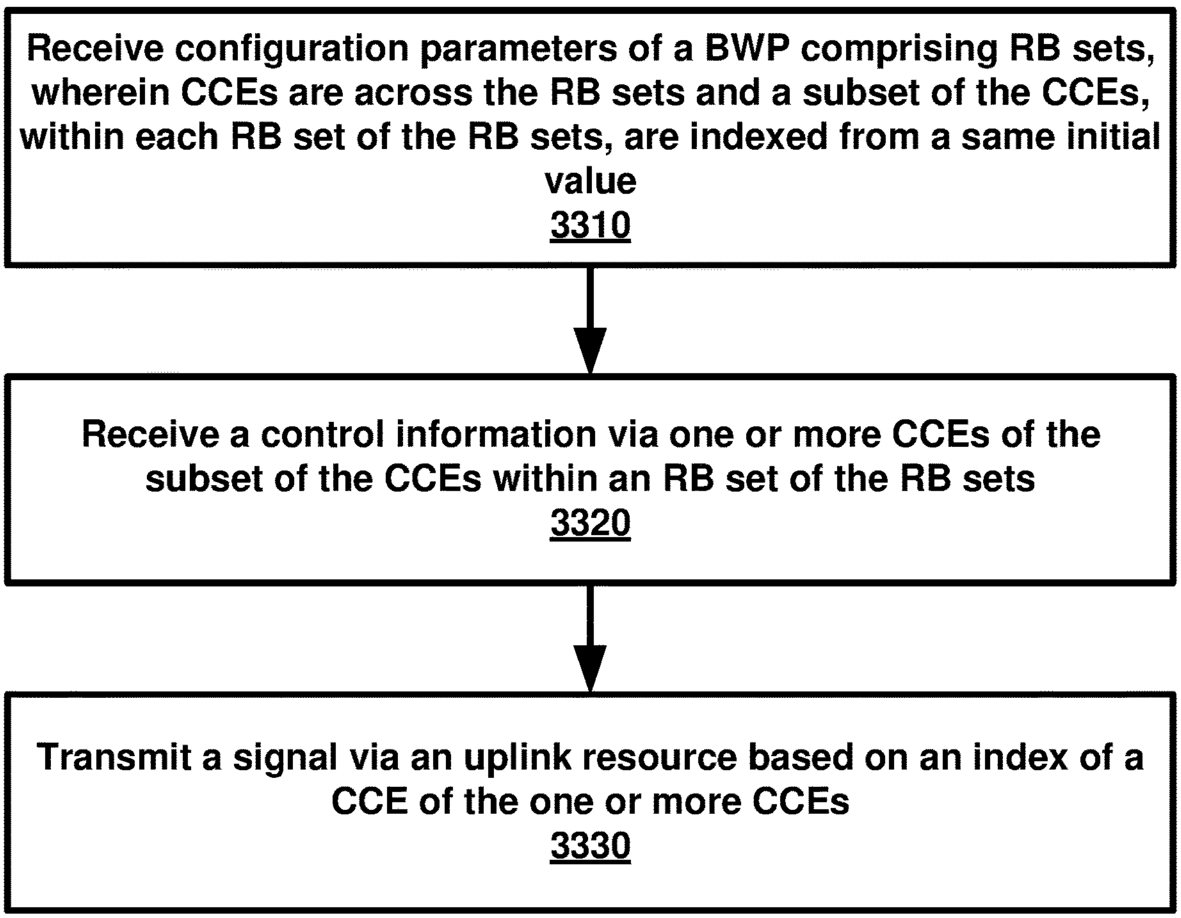

Receive configuration parameters of a BWP comprising RB sets, wherein CCEs are across the RB sets and a subset of the CCEs, within each RB set of the RB sets, are indexed from a same initial value
3310
Receive a control information via one or more CCEs of the subset of the CCEs within an RB set of the RB sets
3320
Transmit a signal via an uplink resource based on an index of a CCE of the one or more CCEs
3330

FIG. 33

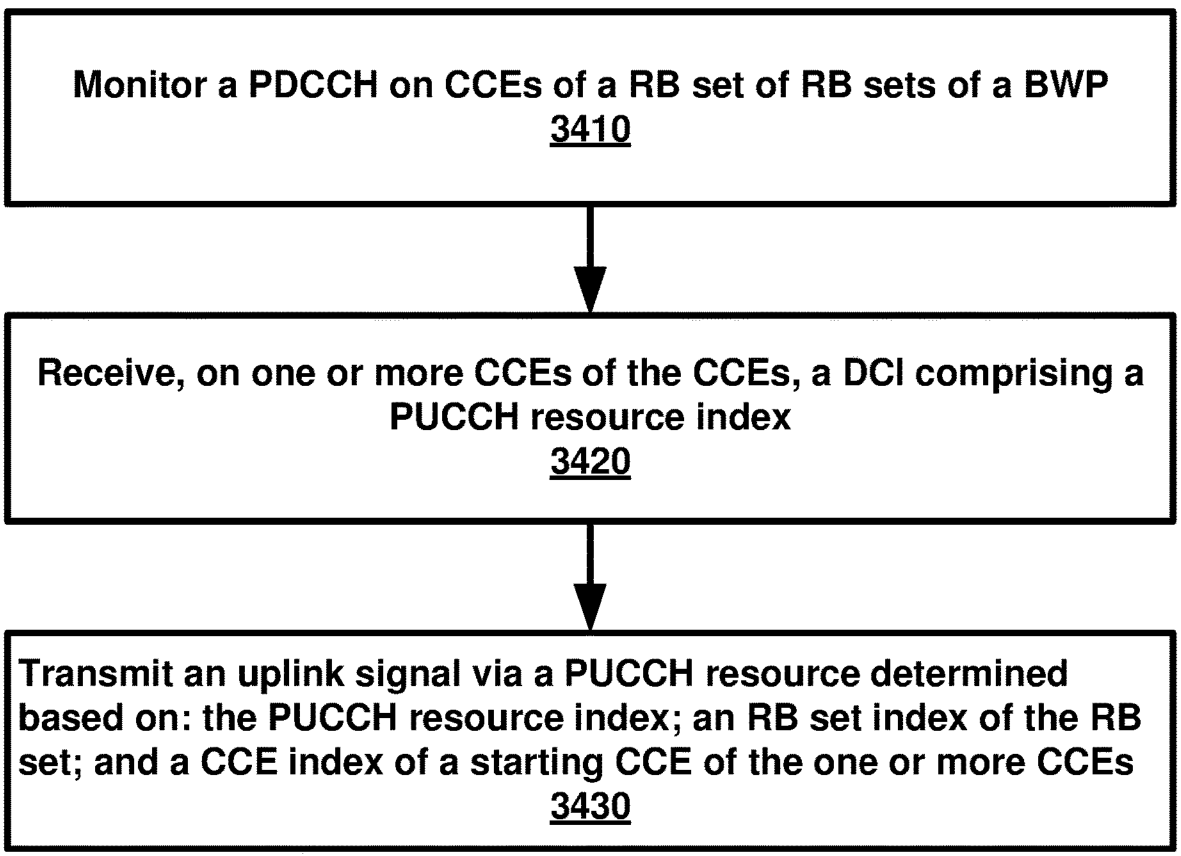

Monitor a PDCCH on CCEs of a RB set of RB sets of a BWP
3410
Receive, on one or more CCEs of the CCEs, a DCI comprising a PUCCH resource index
3420
Transmit an uplink signal via a PUCCH resource determined based on: the PUCCH resource index; an RB set index of the RB set; and a CCE index of a starting CCE of the one or more CCEs
3430

FIG. 34

CONTROL CHANNEL ELEMENT INDEXING FOR UPLINK TRANSMISSION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 17/519,102, filed Nov. 4, 2021, which is a continuation of International Appln. No. PCT/US2020/058814, filed Nov. 4, 2020, which claims the benefit of U.S. Provisional Appln. No. 62/930,130, filed Nov. 4, 2019, the contents of each of which are hereby incorporated by reference in their entireties.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of several of the various embodiments of the present disclosure are described herein with reference to the drawings.

FIG. **1**A and FIG. **1**B illustrate example mobile communication networks in which embodiments of the present disclosure may be implemented.

FIG. **2**A and FIG. **2**B respectively illustrate a New Radio (NR) user plane and control plane protocol stack.

FIG. **3** illustrates an example of services provided between protocol layers of the NR user plane protocol stack of FIG. **2**A.

FIG. **4**A illustrates an example downlink data flow through the NR user plane protocol stack of FIG. **2**A.

FIG. **4**B illustrates an example format of a MAC subheader in a MAC PDU.

FIG. **5**A and FIG. **5**B respectively illustrate a mapping between logical channels, transport channels, and physical channels for the downlink and uplink.

FIG. **6** is an example diagram showing RRC state transitions of a UE.

FIG. **7** illustrates an example configuration of an NR frame into which OFDM symbols are grouped.

FIG. **8** illustrates an example configuration of a slot in the time and frequency domain for an NR carrier.

FIG. **9** illustrates an example of bandwidth adaptation using three configured BWPs for an NR carrier.

FIG. **10**A illustrates three carrier aggregation configurations with two component carriers.

FIG. **10**B illustrates an example of how aggregated cells may be configured into one or more PUCCH groups.

FIG. **11**A illustrates an example of an SS/PBCH block structure and location.

FIG. **11**B illustrates an example of CSI-RSs that are mapped in the time and frequency domains.

FIG. **12**A and FIG. **12**B respectively illustrate examples of three downlink and uplink beam management procedures.

FIG. **13**A, FIG. **13**B, and FIG. **13**C respectively illustrate a four-step contention-based random access procedure, a two-step contention-free random access procedure, and another two-step random access procedure.

FIG. **14**A illustrates an example of CORESET configurations for a bandwidth part.

FIG. **14**B illustrates an example of a CCE-to-REG mapping for DCI transmission on a CORESET and PDCCH processing.

FIG. **15** illustrates an example of a wireless device in communication with a base station.

FIG. **16**A, FIG. **16**B, FIG. **16**C, and FIG. **16**D illustrate example structures for uplink and downlink transmission.

FIG. **17**A, FIG. **17**B and FIG. **17**C show examples of MAC subheaders.

FIG. **18**A shows an example of a DL MAC PDU.

FIG. **18**B shows an example of an UL MAC PDU.

FIG. **19** shows an example of multiple LCIDs of downlink as per an aspect of an example embodiment of the disclosure.

FIG. **20** shows an example of multiple LCIDs of uplink as per an aspect of an example embodiment of the disclosure.

FIG. **21**A and FIG. **21**B show examples of SCell activation/deactivation MAC CEs as per an aspect of an example embodiment of the disclosure.

FIG. **22** shows an example of BWP management as per an aspect of an example embodiment of the disclosure.

FIG. **23** shows an example of search space configuration as per an aspect of an example embodiment of the disclosure.

FIG. **24** shows an example of control resource set configuration as per an aspect of an example embodiment of the disclosure.

FIG. **25**A is a flowchart of downlink transport block delivery as per an aspect of an example embodiment of the disclosure.

FIG. **25**B shows an example of PUCCH resource determination as per an aspect of an example embodiment of the disclosure.

FIG. **26** shows an example of PUCCH resource indication as per an aspect of an example embodiment of the disclosure.

FIG. **27**A shows an example of control resource set (CORESET) configuration as per an aspect of an example embodiment of the disclosure.

FIG. **27**B shows an example of CORESET configuration in a NR-U system as per an aspect of an example embodiment of the disclosure.

FIG. **28** shows an example of PUCCH resource selection as per an aspect of an example embodiment of the disclosure.

FIG. **29** shows an example of PUCCH resource selection as per an aspect of an example embodiment of the disclosure.

FIG. **30** shows an example of PUCCH resource selection as per an aspect of an example embodiment of the disclosure.

FIG. **31** shows an example of PUCCH resource selection as per an aspect of an example embodiment of the disclosure.

FIG. **32** is a flowchart of PUCCH resource selection as per an aspect of an example embodiment of the disclosure.

FIG. **33** is a flowchart of PUCCH resource selection as per an aspect of an example embodiment of the disclosure.

FIG. **34** is a flowchart of PUCCH resource selection as per an aspect of an example embodiment of the disclosure.

DETAILED DESCRIPTION

In the present disclosure, various embodiments are presented as examples of how the disclosed techniques may be implemented and/or how the disclosed techniques may be practiced in environments and scenarios. It will be apparent to persons skilled in the relevant art that various changes in form and detail can be made therein without departing from the scope. In fact, after reading the description, it will be apparent to one skilled in the relevant art how to implement alternative embodiments. The present embodiments should not be limited by any of the described exemplary embodiments. The embodiments of the present disclosure will be described with reference to the accompanying drawings. Limitations, features, and/or elements from the disclosed example embodiments may be combined to create further embodiments within the scope of the disclosure. Any figures which highlight the functionality and advantages, are presented for example purposes only. The disclosed architecture is sufficiently flexible and configurable, such that it may be utilized in ways other than that shown. For example, the actions listed in any flowchart may be re-ordered or only optionally used in some embodiments.

Embodiments may be configured to operate as needed. The disclosed mechanism may be performed when certain criteria are met, for example, in a wireless device, a base station, a radio environment, a network, a combination of the above, and/or the like. Example criteria may be based, at least in part, on for example, wireless device or network node configurations, traffic load, initial system set up, packet sizes, traffic characteristics, a combination of the above, and/or the like. When the one or more criteria are met, various example embodiments may be applied. Therefore, it may be possible to implement example embodiments that selectively implement disclosed protocols.

A base station may communicate with a mix of wireless devices. Wireless devices and/or base stations may support multiple technologies, and/or multiple releases of the same technology. Wireless devices may have some specific capability(ies) depending on wireless device category and/or capability(ies). When this disclosure refers to a base station communicating with a plurality of wireless devices, this disclosure may refer to a subset of the total wireless devices in a coverage area. This disclosure may refer to, for example, a plurality of wireless devices of a given LTE or 5G release with a given capability and in a given sector of the base station. The plurality of wireless devices in this disclosure may refer to a selected plurality of wireless devices, and/or a subset of total wireless devices in a coverage area which perform according to disclosed methods, and/or the like. There may be a plurality of base stations or a plurality of wireless devices in a coverage area that may not comply with the disclosed methods, for example, those wireless devices or base stations may perform based on older releases of LTE or 5G technology.

In this disclosure, "a" and "an" and similar phrases are to be interpreted as "at least one" and "one or more." Similarly, any term that ends with the suffix "(s)" is to be interpreted as "at least one" and "one or more." In this disclosure, the term "may" is to be interpreted as "may, for example." In other words, the term "may" is indicative that the phrase following the term "may" is an example of one of a multitude of suitable possibilities that may, or may not, be employed by one or more of the various embodiments. The terms "comprises" and "consists of", as used herein, enumerate one or more components of the element being described. The term "comprises" is interchangeable with "includes" and does not exclude unenumerated components from being included in the element being described. By contrast, "consists of" provides a complete enumeration of the one or more components of the element being described. The term "based on", as used herein, should be interpreted as "based at least in part on" rather than, for example, "based solely on". The term "and/or" as used herein represents any possible combination of enumerated elements. For example, "A, B, and/or C" may represent A; B; C; A and B; A and C; B and C; or A, B, and C.

If A and B are sets and every element of A is an element of B, A is called a subset of B. In this specification, only non-empty sets and subsets are considered. For example, possible subsets of B={cell1, cell2} are: {cell1}, {cell2}, and {cell1, cell2}. The phrase "based on" (or equally "based at least on") is indicative that the phrase following the term "based on" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments. The phrase "in response to" (or equally "in response at least to") is indicative that the phrase following the phrase "in response to" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments. The phrase "depending on" (or equally "depending at least to") is indicative that the phrase following the phrase "depending on" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments. The phrase "employing/using" (or equally "employing/using at least") is indicative that the phrase following the phrase "employing/using" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments.

The term configured may relate to the capacity of a device whether the device is in an operational or non-operational state. Configured may refer to specific settings in a device that effect the operational characteristics of the device whether the device is in an operational or non-operational state. In other words, the hardware, software, firmware, registers, memory values, and/or the like may be "configured" within a device, whether the device is in an operational or nonoperational state, to provide the device with specific characteristics. Terms such as "a control message to cause in a device" may mean that a control message has parameters that may be used to configure specific characteristics or may be used to implement certain actions in the device, whether the device is in an operational or non-operational state.

In this disclosure, parameters (or equally called, fields, or Information elements: IEs) may comprise one or more information objects, and an information object may comprise one or more other objects. For example, if parameter (IE) N comprises parameter (IE) M, and parameter (IE) M comprises parameter (IE) K, and parameter (IE) K comprises parameter (information element) J. Then, for example, N comprises K, and N comprises J. In an example embodiment, when one or more messages comprise a plurality of parameters, it implies that a parameter in the plurality of parameters is in at least one of the one or more messages, but does not have to be in each of the one or more messages.

Many features presented are described as being optional through the use of "may" or the use of parentheses. For the sake of brevity and legibility, the present disclosure does not explicitly recite each and every permutation that may be obtained by choosing from the set of optional features. The present disclosure is to be interpreted as explicitly disclosing all such permutations. For example, a system described as having three optional features may be embodied in seven ways, namely with just one of the three possible features, with any two of the three possible features or with three of the three possible features.

Many of the elements described in the disclosed embodiments may be implemented as modules. A module is defined here as an element that performs a defined function and has a defined interface to other elements. The modules described in this disclosure may be implemented in hardware, software in combination with hardware, firmware, wetware (e.g. hardware with a biological element) or a combination thereof, which may be behaviorally equivalent. For example, modules may be implemented as a software routine written in a computer language configured to be executed by a hardware machine (such as C, C++, Fortran, Java, Basic, Matlab or the like) or a modeling/simulation program such as Simulink, Stateflow, GNU Octave, or LabVIEWMathScript. It may be possible to implement modules using physical hardware that incorporates discrete or programmable analog, digital and/or quantum hardware. Examples of programmable hardware comprise: computers, microcontrollers, microprocessors, application-specific integrated circuits (ASICs); field programmable gate arrays (FPGAs); and complex programmable logic devices (CPLDs). Computers, microcontrollers and microprocessors are programmed using languages such as assembly, C, C++ or the like. FPGAs, ASICs and CPLDs are often programmed using hardware description languages (HDL) such as VHSIC hardware description language (VHDL) or Verilog that configure connections between internal hardware modules with lesser functionality on a programmable device. The mentioned technologies are often used in combination to achieve the result of a functional module.

FIG. **1**A illustrates an example of a mobile communication network **100** in which embodiments of the present disclosure may be implemented. The mobile communication network **100** may be, for example, a public land mobile network (PLMN) run by a network operator. As illustrated in FIG. **1**A, the mobile communication network **100** includes a core network (CN) **102**, a radio access network (RAN) **104**, and a wireless device **106**.

The CN **102** may provide the wireless device **106** with an interface to one or more data networks (DNs), such as public DNs (e.g., the Internet), private DNs, and/or intra-operator DNs. As part of the interface functionality, the CN **102** may set up end-to-end connections between the wireless device **106** and the one or more DNs, authenticate the wireless device **106**, and provide charging functionality.

The RAN **104** may connect the CN **102** to the wireless device **106** through radio communications over an air interface. As part of the radio communications, the RAN **104** may provide scheduling, radio resource management, and retransmission protocols. The communication direction from the RAN **104** to the wireless device **106** over the air interface is known as the downlink and the communication direction from the wireless device **106** to the RAN **104** over the air interface is known as the uplink. Downlink transmissions may be separated from uplink transmissions using frequency division duplexing (FDD), time-division duplexing (TDD), and/or some combination of the two duplexing techniques.

The term wireless device may be used throughout this disclosure to refer to and encompass any mobile device or fixed (non-mobile) device for which wireless communication is needed or usable. For example, a wireless device may be a telephone, smart phone, tablet, computer, laptop, sensor, meter, wearable device, Internet of Things (IoT) device, vehicle roadside unit (RSU), relay node, automobile, and/or any combination thereof. The term wireless device encompasses other terminology, including user equipment (UE), user terminal (UT), access terminal (AT), mobile station, handset, wireless transmit and receive unit (WTRU), and/or wireless communication device.

The RAN **104** may include one or more base stations (not shown). The term base station may be used throughout this disclosure to refer to and encompass a Node B (associated with UMTS and/or 3G standards), an Evolved Node B (eNB, associated with E-UTRA and/or 4G standards), a remote radio head (RRH), a baseband processing unit coupled to one or more RRHs, a repeater node or relay node used to extend the coverage area of a donor node, a Next Generation Evolved Node B (ng-eNB), a Generation Node B (gNB, associated with NR and/or 5G standards), an access point (AP, associated with, for example, WiFi or any other suitable wireless communication standard), and/or any combination thereof. A base station may comprise at least one gNB Central Unit (gNB-CU) and at least one a gNB Distributed Unit (gNB-DU).

A base station included in the RAN **104** may include one or more sets of antennas for communicating with the wireless device **106** over the air interface. For example, one or more of the base stations may include three sets of antennas to respectively control three cells (or sectors). The size of a cell may be determined by a range at which a receiver (e.g., a base station receiver) can successfully receive the transmissions from a transmitter (e.g., a wireless device transmitter) operating in the cell. Together, the cells of the base stations may provide radio coverage to the wireless device **106** over a wide geographic area to support wireless device mobility.

In addition to three-sector sites, other implementations of base stations are possible. For example, one or more of the base stations in the RAN **104** may be implemented as a sectored site with more or less than three sectors. One or more of the base stations in the RAN **104** may be implemented as an access point, as a baseband processing unit coupled to several remote radio heads (RRHs), and/or as a repeater or relay node used to extend the coverage area of a donor node. A baseband processing unit coupled to RRHs may be part of a centralized or cloud RAN architecture, where the baseband processing unit may be either centralized in a pool of baseband processing units or virtualized. A repeater node may amplify and rebroadcast a radio signal received from a donor node. A relay node may perform the same/similar functions as a repeater node but may decode the radio signal received from the donor node to remove noise before amplifying and rebroadcasting the radio signal.

The RAN **104** may be deployed as a homogenous network of macrocell base stations that have similar antenna patterns and similar high-level transmit powers. The RAN **104** may be deployed as a heterogeneous network. In heterogeneous networks, small cell base stations may be used to provide small coverage areas, for example, coverage areas that overlap with the comparatively larger coverage areas provided by macrocell base stations. The small coverage areas may be provided in areas with high data traffic (or so-called "hotspots") or in areas with weak macrocell coverage. Examples of small cell base stations include, in order of decreasing coverage area, microcell base stations, picocell base stations, and femtocell base stations or home base stations.

The Third-Generation Partnership Project (3GPP) was formed in 1998 to provide global standardization of specifications for mobile communication networks similar to the mobile communication network **100** in FIG. **1**A. To date, 3GPP has produced specifications for three generations of mobile networks: a third generation (3G) network known as Universal Mobile Telecommunications System (UMTS), a fourth generation (4G) network known as Long-Term Evolution (LTE), and a fifth generation (5G) network known as 5G System (5GS). Embodiments of the present disclosure are described with reference to the RAN of a 3GPP 5G network, referred to as next-generation RAN (NG-RAN). Embodiments may be applicable to RANs of other mobile communication networks, such as the RAN **104** in FIG. **1**A, the RANs of earlier 3G and 4G networks, and those of future networks yet to be specified (e.g., a 3GPP 6G network). NG-RAN implements 5G radio access technology known as

New Radio (NR) and may be provisioned to implement 4G radio access technology or other radio access technologies, including non-3GPP radio access technologies.

FIG. **1**B illustrates another example mobile communication network **150** in which embodiments of the present disclosure may be implemented. Mobile communication network **150** may be, for example, a PLMN run by a network operator. As illustrated in FIG. **1**B, mobile communication network **150** includes a 5G core network (5G-CN) **152**, an NG-RAN **154**, and UEs **156**A and **156**B (collectively UEs **156**). These components may be implemented and operate in the same or similar manner as corresponding components described with respect to FIG. **1**A.

The 5G-CN **152** provides the UEs **156** with an interface to one or more DNs, such as public DNs (e.g., the Internet), private DNs, and/or intra-operator DNs. As part of the interface functionality, the 5G-CN **152** may set up end-to-end connections between the UEs **156** and the one or more DNs, authenticate the UEs **156**, and provide charging functionality. Compared to the CN of a 3GPP 4G network, the basis of the 5G-CN **152** may be a service-based architecture. This means that the architecture of the nodes making up the 5G-CN **152** may be defined as network functions that offer services via interfaces to other network functions. The network functions of the 5G-CN **152** may be implemented in several ways, including as network elements on dedicated or shared hardware, as software instances running on dedicated or shared hardware, or as virtualized functions instantiated on a platform (e.g., a cloud-based platform).

As illustrated in FIG. **1**B, the 5G-CN **152** includes an Access and Mobility Management Function (AMF) **158**A and a User Plane Function (UPF) **158**B, which are shown as one component AMF/UPF **158** in FIG. **1**B for ease of illustration. The UPF **158**B may serve as a gateway between the NG-RAN **154** and the one or more DNs. The UPF **158**B may perform functions such as packet routing and forwarding, packet inspection and user plane policy rule enforcement, traffic usage reporting, uplink classification to support routing of traffic flows to the one or more DNs, quality of service (QoS) handling for the user plane (e.g., packet filtering, gating, uplink/downlink rate enforcement, and uplink traffic verification), downlink packet buffering, and downlink data notification triggering. The UPF **158**B may serve as an anchor point for intra-/inter-Radio Access Technology (RAT) mobility, an external protocol (or packet) data unit (PDU) session point of interconnect to the one or more DNs, and/or a branching point to support a multi-homed PDU session. The UEs **156** may be configured to receive services through a PDU session, which is a logical connection between a UE and a DN.

The AMF **158**A may perform functions such as Non-Access Stratum (NAS) signaling termination, NAS signaling security, Access Stratum (AS) security control, inter-CN node signaling for mobility between 3GPP access networks, idle mode UE reachability (e.g., control and execution of paging retransmission), registration area management, intra-system and inter-system mobility support, access authentication, access authorization including checking of roaming rights, mobility management control (subscription and policies), network slicing support, and/or session management function (SMF) selection. NAS may refer to the functionality operating between a CN and a UE, and AS may refer to the functionality operating between the UE and a RAN.

The 5G-CN **152** may include one or more additional network functions that are not shown in FIG. **1**B for the sake of clarity. For example, the 5G-CN **152** may include one or more of a Session Management Function (SMF), an NR Repository Function (NRF), a Policy Control Function (PCF), a Network Exposure Function (NEF), a Unified Data Management (UDM), an Application Function (AF), and/or an Authentication Server Function (AUSF).

The NG-RAN **154** may connect the 5G-CN **152** to the UEs **156** through radio communications over the air interface. The NG-RAN **154** may include one or more gNBs, illustrated as gNB **160**A and gNB **160**B (collectively gNBs **160**) and/or one or more ng-eNBs, illustrated as ng-eNB **162**A and ng-eNB **162**B (collectively ng-eNBs **162**). The gNBs **160** and ng-eNBs **162** may be more generically referred to as base stations. The gNBs **160** and ng-eNBs **162** may include one or more sets of antennas for communicating with the UEs **156** over an air interface. For example, one or more of the gNBs **160** and/or one or more of the ng-eNBs **162** may include three sets of antennas to respectively control three cells (or sectors). Together, the cells of the gNBs **160** and the ng-eNBs **162** may provide radio coverage to the UEs **156** over a wide geographic area to support UE mobility.

As shown in FIG. **1**B, the gNBs **160** and/or the ng-eNBs **162** may be connected to the 5G-CN **152** by means of an NG interface and to other base stations by an Xn interface. The NG and Xn interfaces may be established using direct physical connections and/or indirect connections over an underlying transport network, such as an internet protocol (IP) transport network. The gNBs **160** and/or the ng-eNBs **162** may be connected to the UEs **156** by means of a Uu interface. For example, as illustrated in FIG. **1**B, gNB **160**A may be connected to the UE **156**A by means of a Uu interface. The NG, Xn, and Uu interfaces are associated with a protocol stack. The protocol stacks associated with the interfaces may be used by the network elements in FIG. **1**B to exchange data and signaling messages and may include two planes: a user plane and a control plane. The user plane may handle data of interest to a user. The control plane may handle signaling messages of interest to the network elements.

The gNBs **160** and/or the ng-eNBs **162** may be connected to one or more AMF/UPF functions of the 5G-CN **152**, such as the AMF/UPF **158**, by means of one or more NG interfaces. For example, the gNB **160**A may be connected to the UPF **158**B of the AMF/UPF **158** by means of an NG-User plane (NG-U) interface. The NG-U interface may provide delivery (e.g., non-guaranteed delivery) of user plane PDUs between the gNB **160**A and the UPF **158**B. The gNB **160**A may be connected to the AMF **158**A by means of an NG-Control plane (NG-C) interface. The NG-C interface may provide, for example, NG interface management, UE context management, UE mobility management, transport of NAS messages, paging, PDU session management, and configuration transfer and/or warning message transmission.

The gNBs **160** may provide NR user plane and control plane protocol terminations towards the UEs **156** over the Uu interface. For example, the gNB **160**A may provide NR user plane and control plane protocol terminations toward the UE **156**A over a Uu interface associated with a first protocol stack. The ng-eNBs **162** may provide Evolved UMTS Terrestrial Radio Access (E-UTRA) user plane and control plane protocol terminations towards the UEs **156** over a Uu interface, where E-UTRA refers to the 3GPP 4G radio-access technology. For example, the ng-eNB **162**B may provide E-UTRA user plane and control plane protocol terminations towards the UE **156**B over a Uu interface associated with a second protocol stack.

The 5G-CN **152** was described as being configured to handle NR and 4G radio accesses. It will be appreciated by one of ordinary skill in the art that it may be possible for NR to connect to a 4G core network in a mode known as "non-standalone operation." In non-standalone operation, a 4G core network is used to provide (or at least support) control-plane functionality (e.g., initial access, mobility, and paging). Although only one AMF/UPF **158** is shown in FIG. **1**B, one gNB or ng-eNB may be connected to multiple AMF/UPF nodes to provide redundancy and/or to load share across the multiple AMF/UPF nodes.

As discussed, an interface (e.g., Uu, Xn, and NG interfaces) between the network elements in FIG. **1**B may be associated with a protocol stack that the network elements use to exchange data and signaling messages. A protocol stack may include two planes: a user plane and a control plane. The user plane may handle data of interest to a user, and the control plane may handle signaling messages of interest to the network elements.

FIG. **2**A and FIG. **2**B respectively illustrate examples of NR user plane and NR control plane protocol stacks for the Uu interface that lies between a UE **210** and a gNB **220**. The protocol stacks illustrated in FIG. **2**A and FIG. **2**B may be the same or similar to those used for the Uu interface between, for example, the UE **156**A and the gNB **160**A shown in FIG. **1**B.

FIG. **2**A illustrates a NR user plane protocol stack comprising five layers implemented in the UE **210** and the gNB **220**. At the bottom of the protocol stack, physical layers (PHYs) **211** and **221** may provide transport services to the higher layers of the protocol stack and may correspond to layer 1 of the Open Systems Interconnection (OSI) model. The next four protocols above PHYs **211** and **221** comprise media access control layers (MACs) **212** and **222**, radio link control layers (RLCs) **213** and **223**, packet data convergence protocol layers (PDCPs) **214** and **224**, and service data application protocol layers (SDAPs) **215** and **225**. Together, these four protocols may make up layer 2, or the data link layer, of the OSI model.

FIG. **3** illustrates an example of services provided between protocol layers of the NR user plane protocol stack. Starting from the top of FIG. **2**A and FIG. **3**, the SDAPs **215** and **225** may perform QoS flow handling. The UE **210** may receive services through a PDU session, which may be a logical connection between the UE **210** and a DN. The PDU session may have one or more QoS flows. A UPF of a CN (e.g., the UPF **158**B) may map IP packets to the one or more QoS flows of the PDU session based on QoS requirements (e.g., in terms of delay, data rate, and/or error rate). The SDAPs **215** and **225** may perform mapping/de-mapping between the one or more QoS flows and one or more data radio bearers. The mapping/de-mapping between the QoS flows and the data radio bearers may be determined by the SDAP **225** at the gNB **220**. The SDAP **215** at the UE **210** may be informed of the mapping between the QoS flows and the data radio bearers through reflective mapping or control signaling received from the gNB **220**. For reflective mapping, the SDAP **225** at the gNB **220** may mark the downlink packets with a QoS flow indicator (QFI), which may be observed by the SDAP **215** at the UE **210** to determine the mapping/de-mapping between the QoS flows and the data radio bearers.

The PDCPs **214** and **224** may perform header compression/decompression to reduce the amount of data that needs to be transmitted over the air interface, ciphering/deciphering to prevent unauthorized decoding of data transmitted over the air interface, and integrity protection (to ensure control messages originate from intended sources. The PDCPs **214** and **224** may perform retransmissions of undelivered packets, in-sequence delivery and reordering of packets, and removal of packets received in duplicate due to, for example, an intra-gNB handover. The PDCPs **214** and **224** may perform packet duplication to improve the likelihood of the packet being received and, at the receiver, remove any duplicate packets. Packet duplication may be useful for services that require high reliability.

Although not shown in FIG. **3**, PDCPs **214** and **224** may perform mapping/de-mapping between a split radio bearer and RLC channels in a dual connectivity scenario. Dual connectivity is a technique that allows a UE to connect to two cells or, more generally, two cell groups: a master cell group (MCG) and a secondary cell group (SCG). A split bearer is when a single radio bearer, such as one of the radio bearers provided by the PDCPs **214** and **224** as a service to the SDAPs **215** and **225**, is handled by cell groups in dual connectivity. The PDCPs **214** and **224** may map/de-map the split radio bearer between RLC channels belonging to cell groups.

The RLCs **213** and **223** may perform segmentation, retransmission through Automatic Repeat Request (ARQ), and removal of duplicate data units received from MACs **212** and **222**, respectively. The RLCs **213** and **223** may support three transmission modes: transparent mode (TM); unacknowledged mode (UM); and acknowledged mode (AM). Based on the transmission mode an RLC is operating, the RLC may perform one or more of the noted functions. The RLC configuration may be per logical channel with no dependency on numerologies and/or Transmission Time Interval (TTI) durations. As shown in FIG. **3**, the RLCs **213** and **223** may provide RLC channels as a service to PDCPs **214** and **224**, respectively.

The MACs **212** and **222** may perform multiplexing/demultiplexing of logical channels and/or mapping between logical channels and transport channels. The multiplexing/demultiplexing may include multiplexing/demultiplexing of data units, belonging to the one or more logical channels, into/from Transport Blocks (TBs) delivered to/from the PHYs **211** and **221**. The MAC **222** may be configured to perform scheduling, scheduling information reporting, and priority handling between UEs by means of dynamic scheduling. Scheduling may be performed in the gNB **220** (at the MAC **222**) for downlink and uplink. The MACs **212** and **222** may be configured to perform error correction through Hybrid Automatic Repeat Request (HARQ) (e.g., one HARQ entity per carrier in case of Carrier Aggregation (CA)), priority handling between logical channels of the UE **210** by means of logical channel prioritization, and/or padding. The MACs **212** and **222** may support one or more numerologies and/or transmission timings. In an example, mapping restrictions in a logical channel prioritization may control which numerology and/or transmission timing a logical channel may use. As shown in FIG. **3**, the MACs **212** and **222** may provide logical channels as a service to the RLCs **213** and **223**.

The PHYs **211** and **221** may perform mapping of transport channels to physical channels and digital and analog signal processing functions for sending and receiving information over the air interface. These digital and analog signal processing functions may include, for example, coding/decoding and modulation/demodulation. The PHYs **211** and **221** may perform multi-antenna mapping. As shown in FIG. **3**, the PHYs **211** and **221** may provide one or more transport channels as a service to the MACs **212** and **222**.

FIG. **4**A illustrates an example downlink data flow through the NR user plane protocol stack. FIG. **4**A illustrates a downlink data flow of three IP packets (n, n+1, and m) through the NR user plane protocol stack to generate two TBs at the gNB **220**. An uplink data flow through the NR user plane protocol stack may be similar to the downlink data flow depicted in FIG. **4**A.

The downlink data flow of FIG. **4**A begins when SDAP **225** receives the three IP packets from one or more QoS flows and maps the three packets to radio bearers. In FIG. **4**A, the SDAP **225** maps IP packets n and n+1 to a first radio bearer **402** and maps IP packet m to a second radio bearer **404**. An SDAP header (labeled with an "H" in FIG. **4**A) is added to an IP packet. The data unit from/to a higher protocol layer is referred to as a service data unit (SDU) of the lower protocol layer and the data unit to/from a lower protocol layer is referred to as a protocol data unit (PDU) of the higher protocol layer. As shown in FIG. **4**A, the data unit from the SDAP **225** is an SDU of lower protocol layer PDCP **224** and is a PDU of the SDAP **225**.

The remaining protocol layers in FIG. **4**A may perform their associated functionality (e.g., with respect to FIG. **3**), add corresponding headers, and forward their respective outputs to the next lower layer. For example, the PDCP **224** may perform IP-header compression and ciphering and forward its output to the RLC **223**. The RLC **223** may optionally perform segmentation (e.g., as shown for IP packet m in FIG. **4**A) and forward its output to the MAC **222**. The MAC **222** may multiplex a number of RLC PDUs and may attach a MAC subheader to an RLC PDU to form a transport block. In NR, the MAC subheaders may be distributed across the MAC PDU, as illustrated in FIG. **4**A. In LTE, the MAC subheaders may be entirely located at the beginning of the MAC PDU. The NR MAC PDU structure may reduce processing time and associated latency because the MAC PDU subheaders may be computed before the full MAC PDU is assembled.

FIG. **4**B illustrates an example format of a MAC subheader in a MAC PDU. The MAC subheader includes: an SDU length field for indicating the length (e.g., in bytes) of the MAC SDU to which the MAC subheader corresponds; a logical channel identifier (LCD) field for identifying the logical channel from which the MAC SDU originated to aid in the demultiplexing process; a flag (F) for indicating the size of the SDU length field; and a reserved bit (R) field for future use.

FIG. **4**B further illustrates MAC control elements (CEs) inserted into the MAC PDU by a MAC, such as MAC **223** or MAC **222**. For example, FIG. **4**B illustrates two MAC CEs inserted into the MAC PDU. MAC CEs may be inserted at the beginning of a MAC PDU for downlink transmissions (as shown in FIG. **4**B) and at the end of a MAC PDU for uplink transmissions. MAC CEs may be used for in-band control signaling. Example MAC CEs include: scheduling-related MAC CEs, such as buffer status reports and power headroom reports; activation/deactivation MAC CEs, such as those for activation/deactivation of PDCP duplication detection, channel state information (CSI) reporting, sounding reference signal (SRS) transmission, and prior configured components; discontinuous reception (DRX) related MAC CEs; timing advance MAC CEs; and random access related MAC CEs. A MAC CE may be preceded by a MAC subheader with a similar format as described for MAC SDUs and may be identified with a reserved value in the LCID field that indicates the type of control information included in the MAC CE.

Before describing the NR control plane protocol stack, logical channels, transport channels, and physical channels are first described as well as a mapping between the channel types. One or more of the channels may be used to carry out functions associated with the NR control plane protocol stack described later below.

FIG. **5**A and FIG. **5**B illustrate, for downlink and uplink respectively, a mapping between logical channels, transport channels, and physical channels. Information is passed through channels between the RLC, the MAC, and the PHY of the NR protocol stack. A logical channel may be used between the RLC and the MAC and may be classified as a control channel that carries control and configuration information in the NR control plane or as a traffic channel that carries data in the NR user plane. A logical channel may be classified as a dedicated logical channel that is dedicated to a specific UE or as a common logical channel that may be used by more than one UE. A logical channel may also be defined by the type of information it carries. The set of logical channels defined by NR include, for example:

- a paging control channel (PCCH) for carrying paging messages used to page a UE whose location is not known to the network on a cell level;
- a broadcast control channel (BCCH) for carrying system information messages in the form of a master information block (MIB) and several system information blocks (SIBs), wherein the system information messages may be used by the UEs to obtain information about how a cell is configured and how to operate within the cell;
- a common control channel (CCCH) for carrying control messages together with random access;
- a dedicated control channel (DCCH) for carrying control messages to/from a specific the UE to configure the UE; and
- a dedicated traffic channel (DTCH) for carrying user data to/from a specific the UE.

Transport channels are used between the MAC and PHY layers and may be defined by how the information they carry is transmitted over the air interface. The set of transport channels defined by NR include, for example:

- a paging channel (PCH) for carrying paging messages that originated from the PCCH;
- a broadcast channel (BCH) for carrying the MIB from the BCCH;
- a downlink shared channel (DL-SCH) for carrying downlink data and signaling messages, including the SIBs from the BCCH;
- an uplink shared channel (UL-SCH) for carrying uplink data and signaling messages; and
- a random access channel (RACH) for allowing a UE to contact the network without any prior scheduling.

The PHY may use physical channels to pass information between processing levels of the PHY. A physical channel may have an associated set of time-frequency resources for carrying the information of one or more transport channels. The PHY may generate control information to support the low-level operation of the PHY and provide the control information to the lower levels of the PHY via physical control channels, known as L1/L2 control channels. The set of physical channels and physical control channels defined by NR include, for example:

- a physical broadcast channel (PBCH) for carrying the MIB from the BCH;
- a physical downlink shared channel (PDSCH) for carrying downlink data and signaling messages from the DL-SCH, as well as paging messages from the PCH;
- a physical downlink control channel (PDCCH) for carrying downlink control information (DCI), which may

include downlink scheduling commands, uplink scheduling grants, and uplink power control commands;

a physical uplink shared channel (PUSCH) for carrying uplink data and signaling messages from the UL-SCH and in some instances uplink control information (UCI) as described below;

a physical uplink control channel (PUCCH) for carrying UCI, which may include HARQ acknowledgments, channel quality indicators (CQI), pre-coding matrix indicators (PMI), rank indicators (RI), and scheduling requests (SR); and

a physical random access channel (PRACH) for random access.

Similar to the physical control channels, the physical layer generates physical signals to support the low-level operation of the physical layer. As shown in FIG. **5**A and FIG. **5**B, the physical layer signals defined by NR include: primary synchronization signals (PSS), secondary synchronization signals (SSS), channel state information reference signals (CSI-RS), demodulation reference signals (DMRS), sounding reference signals (SRS), and phase-tracking reference signals (PT-RS). These physical layer signals will be described in greater detail below.

FIG. **2**B illustrates an example NR control plane protocol stack. As shown in FIG. **2**B, the NR control plane protocol stack may use the same/similar first four protocol layers as the example NR user plane protocol stack. These four protocol layers include the PHYs **211** and **221**, the MACs **212** and **222**, the RLCs **213** and **223**, and the PDCPs **214** and **224**. Instead of having the SDAPs **215** and **225** at the top of the stack as in the NR user plane protocol stack, the NR control plane stack has radio resource controls (RRCs) **216** and **226** and NAS protocols **217** and **237** at the top of the NR control plane protocol stack.

The NAS protocols **217** and **237** may provide control plane functionality between the UE **210** and the AMF **230** (e.g., the AMF **158**A) or, more generally, between the UE **210** and the CN. The NAS protocols **217** and **237** may provide control plane functionality between the UE **210** and the AMF **230** via signaling messages, referred to as NAS messages. There is no direct path between the UE **210** and the AMF **230** through which the NAS messages can be transported. The NAS messages may be transported using the AS of the Uu and NG interfaces. NAS protocols **217** and **237** may provide control plane functionality such as authentication, security, connection setup, mobility management, and session management.

The RRCs **216** and **226** may provide control plane functionality between the UE **210** and the gNB **220** or, more generally, between the UE **210** and the RAN. The RRCs **216** and **226** may provide control plane functionality between the UE **210** and the gNB **220** via signaling messages, referred to as RRC messages. RRC messages may be transmitted between the UE **210** and the RAN using signaling radio bearers and the same/similar PDCP, RLC, MAC, and PHY protocol layers. The MAC may multiplex control-plane and user-plane data into the same transport block (TB). The RRCs **216** and **226** may provide control plane functionality such as: broadcast of system information related to AS and NAS; paging initiated by the CN or the RAN; establishment, maintenance and release of an RRC connection between the UE **210** and the RAN; security functions including key management; establishment, configuration, maintenance and release of signaling radio bearers and data radio bearers; mobility functions; QoS management functions; the UE measurement reporting and control of the reporting; detection of and recovery from radio link failure (RLF); and/or NAS message transfer. As part of establishing an RRC connection, RRCs **216** and **226** may establish an RRC context, which may involve configuring parameters for communication between the UE **210** and the RAN.

FIG. **6** is an example diagram showing RRC state transitions of a UE. The UE may be the same or similar to the wireless device **106** depicted in FIG. **1**A, the UE **210** depicted in FIG. **2**A and FIG. **2**B, or any other wireless device described in the present disclosure. As illustrated in FIG. **6**, a UE may be in at least one of three RRC states: RRC connected **602** (e.g., RRC_CONNECTED), RRC idle **604** (e.g., RRC_IDLE), and RRC inactive **606** (e.g., RRC_INACTIVE).

In RRC connected **602**, the UE has an established RRC context and may have at least one RRC connection with a base station. The base station may be similar to one of the one or more base stations included in the RAN **104** depicted in FIG. **1**A, one of the gNBs **160** or ng-eNBs **162** depicted in FIG. **1**B, the gNB **220** depicted in FIG. **2**A and FIG. **2**B, or any other base station described in the present disclosure. The base station with which the UE is connected may have the RRC context for the UE. The RRC context, referred to as the UE context, may comprise parameters for communication between the UE and the base station. These parameters may include, for example: one or more AS contexts; one or more radio link configuration parameters; bearer configuration information (e.g., relating to a data radio bearer, signaling radio bearer, logical channel, QoS flow, and/or PDU session); security information; and/or PHY, MAC, RLC, PDCP, and/or SDAP layer configuration information. While in RRC connected **602**, mobility of the UE may be managed by the RAN (e.g., the RAN **104** or the NG-RAN **154**). The UE may measure the signal levels (e.g., reference signal levels) from a serving cell and neighboring cells and report these measurements to the base station currently serving the UE. The UE's serving base station may request a handover to a cell of one of the neighboring base stations based on the reported measurements. The RRC state may transition from RRC connected **602** to RRC idle **604** through a connection release procedure **608** or to RRC inactive **606** through a connection inactivation procedure **610**.

In RRC idle **604**, an RRC context may not be established for the UE. In RRC idle **604**, the UE may not have an RRC connection with the base station. While in RRC idle **604**, the UE may be in a sleep state for the majority of the time (e.g., to conserve battery power). The UE may wake up periodically (e.g., once in every discontinuous reception cycle) to monitor for paging messages from the RAN. Mobility of the UE may be managed by the UE through a procedure known as cell reselection. The RRC state may transition from RRC idle **604** to RRC connected **602** through a connection establishment procedure **612**, which may involve a random access procedure as discussed in greater detail below.

In RRC inactive **606**, the RRC context previously established is maintained in the UE and the base station. This allows for a fast transition to RRC connected **602** with reduced signaling overhead as compared to the transition from RRC idle **604** to RRC connected **602**. While in RRC inactive **606**, the UE may be in a sleep state and mobility of the UE may be managed by the UE through cell reselection. The RRC state may transition from RRC inactive **606** to RRC connected **602** through a connection resume procedure **614** or to RRC idle **604** though a connection release procedure **616** that may be the same as or similar to connection release procedure **608**.

An RRC state may be associated with a mobility management mechanism. In RRC idle **604** and RRC inactive **606**, mobility is managed by the UE through cell reselection. The purpose of mobility management in RRC idle **604** and RRC inactive **606** is to allow the network to be able to notify the UE of an event via a paging message without having to broadcast the paging message over the entire mobile communications network. The mobility management mechanism used in RRC idle **604** and RRC inactive **606** may allow the network to track the UE on a cell-group level so that the paging message may be broadcast over the cells of the cell group that the UE currently resides within instead of the entire mobile communication network. The mobility management mechanisms for RRC idle **604** and RRC inactive **606** track the UE on a cell-group level. They may do so using different granularities of grouping. For example, there may be three levels of cell-grouping granularity: individual cells; cells within a RAN area identified by a RAN area identifier (RAI); and cells within a group of RAN areas, referred to as a tracking area and identified by a tracking area identifier (TAI).

Tracking areas may be used to track the UE at the CN level. The CN (e.g., the CN **102** or the 5G-CN **152**) may provide the UE with a list of TAIs associated with a UE registration area. If the UE moves, through cell reselection, to a cell associated with a TAI not included in the list of TAIs associated with the UE registration area, the UE may perform a registration update with the CN to allow the CN to update the UE's location and provide the UE with a new the UE registration area.

RAN areas may be used to track the UE at the RAN level. For a UE in RRC inactive **606** state, the UE may be assigned a RAN notification area. A RAN notification area may comprise one or more cell identities, a list of RAIs, or a list of TAIs. In an example, a base station may belong to one or more RAN notification areas. In an example, a cell may belong to one or more RAN notification areas. If the UE moves, through cell reselection, to a cell not included in the RAN notification area assigned to the UE, the UE may perform a notification area update with the RAN to update the UE's RAN notification area.

A base station storing an RRC context for a UE or a last serving base station of the UE may be referred to as an anchor base station. An anchor base station may maintain an RRC context for the UE at least during a period of time that the UE stays in a RAN notification area of the anchor base station and/or during a period of time that the UE stays in RRC inactive **606**.

A gNB, such as gNBs **160** in FIG. **1**B, may be split in two parts: a central unit (gNB-CU), and one or more distributed units (gNB-DU). A gNB-CU may be coupled to one or more gNB-DUs using an F1 interface. The gNB-CU may comprise the RRC, the PDCP, and the SDAP. A gNB-DU may comprise the RLC, the MAC, and the PHY.

In NR, the physical signals and physical channels (discussed with respect to FIG. **5**A and FIG. **5**B) may be mapped onto orthogonal frequency divisional multiplexing (OFDM) symbols. OFDM is a multicarrier communication scheme that transmits data over F orthogonal subcarriers (or tones). Before transmission, the data may be mapped to a series of complex symbols (e.g., M-quadrature amplitude modulation (M-QAM) or M-phase shift keying (M-PSK) symbols), referred to as source symbols, and divided into F parallel symbol streams. The F parallel symbol streams may be treated as though they are in the frequency domain and used as inputs to an Inverse Fast Fourier Transform (IFFT) block that transforms them into the time domain. The IFFT block may take in F source symbols at a time, one from each of the F parallel symbol streams, and use each source symbol to modulate the amplitude and phase of one of F sinusoidal basis functions that correspond to the F orthogonal subcarriers. The output of the IFFT block may be F time-domain samples that represent the summation of the F orthogonal subcarriers. The F time-domain samples may form a single OFDM symbol. After some processing (e.g., addition of a cyclic prefix) and up-conversion, an OFDM symbol provided by the IFFT block may be transmitted over the air interface on a carrier frequency. The F parallel symbol streams may be mixed using an FFT block before being processed by the IFFT block. This operation produces Discrete Fourier Transform (DFT)-precoded OFDM symbols and may be used by UEs in the uplink to reduce the peak to average power ratio (PAPR). Inverse processing may be performed on the OFDM symbol at a receiver using an FFT block to recover the data mapped to the source symbols.

FIG. **7** illustrates an example configuration of an NR frame into which OFDM symbols are grouped. An NR frame may be identified by a system frame number (SFN). The SFN may repeat with a period of 1024 frames. As illustrated, one NR frame may be 10 milliseconds (ms) in duration and may include 10 subframes that are 1 ms in duration. A subframe may be divided into slots that include, for example, 14 OFDM symbols per slot.

The duration of a slot may depend on the numerology used for the OFDM symbols of the slot. In NR, a flexible numerology is supported to accommodate different cell deployments (e.g., cells with carrier frequencies below 1 GHz up to cells with carrier frequencies in the mm-wave range). A numerology may be defined in terms of subcarrier spacing and cyclic prefix duration. For a numerology in NR, subcarrier spacings may be scaled up by powers of two from a baseline subcarrier spacing of 15 kHz, and cyclic prefix durations may be scaled down by powers of two from a baseline cyclic prefix duration of 4.7 μs. For example, NR defines numerologies with the following subcarrier spacing/cyclic prefix duration combinations: 15 kHz/4.7 μs; 30 kHz/2.3 μs; 60 kHz/1.2 μs; 120 kHz/0.59 μs; and 240 kHz/0.29 μs.

A slot may have a fixed number of OFDM symbols (e.g., 14 OFDM symbols). A numerology with a higher subcarrier spacing has a shorter slot duration and, correspondingly, more slots per subframe. FIG. **7** illustrates this numerology-dependent slot duration and slots-per-subframe transmission structure (the numerology with a subcarrier spacing of 240 kHz is not shown in FIG. **7** for ease of illustration). A subframe in NR may be used as a numerology-independent time reference, while a slot may be used as the unit upon which uplink and downlink transmissions are scheduled. To support low latency, scheduling in NR may be decoupled from the slot duration and start at any OFDM symbol and last for as many symbols as needed for a transmission. These partial slot transmissions may be referred to as mini-slot or subslot transmissions.

FIG. **8** illustrates an example configuration of a slot in the time and frequency domain for an NR carrier. The slot includes resource elements (REs) and resource blocks (RBs). An RE is the smallest physical resource in NR. An RE spans one OFDM symbol in the time domain by one subcarrier in the frequency domain as shown in FIG. **8**. An RB spans twelve consecutive REs in the frequency domain as shown in FIG. **8**. An NR carrier may be limited to a width of 275 RBs or 275×12=3300 subcarriers. Such a limitation, if used, may limit the NR carrier to 50, 100, 200, and 400 MHz for subcarrier spacings of 15, 30, 60, and 120 kHz, respectively, where the 400 MHz bandwidth may be set based on a 400 MHz per carrier bandwidth limit.

FIG. **8** illustrates a single numerology being used across the entire bandwidth of the NR carrier. In other example configurations, multiple numerologies may be supported on the same carrier.

NR may support wide carrier bandwidths (e.g., up to 400 MHz for a subcarrier spacing of 120 kHz). Not all UEs may be able to receive the full carrier bandwidth (e.g., due to hardware limitations). Also, receiving the full carrier bandwidth may be prohibitive in terms of UE power consumption. In an example, to reduce power consumption and/or for other purposes, a UE may adapt the size of the UE's receive bandwidth based on the amount of traffic the UE is scheduled to receive. This is referred to as bandwidth adaptation.

NR defines bandwidth parts (BWPs) to support UEs not capable of receiving the full carrier bandwidth and to support bandwidth adaptation. In an example, a BWP may be defined by a subset of contiguous RBs on a carrier. A UE may be configured (e.g., via RRC layer) with one or more downlink BWPs and one or more uplink BWPs per serving cell (e.g., up to four downlink BWPs and up to four uplink BWPs per serving cell). At a given time, one or more of the configured BWPs for a serving cell may be active. These one or more BWPs may be referred to as active BWPs of the serving cell. When a serving cell is configured with a secondary uplink carrier, the serving cell may have one or more first active BWPs in the uplink carrier and one or more second active BWPs in the secondary uplink carrier.

For unpaired spectra, a downlink BWP from a set of configured downlink BWPs may be linked with an uplink BWP from a set of configured uplink BWPs if a downlink BWP index of the downlink BWP and an uplink BWP index of the uplink BWP are the same. For unpaired spectra, a UE may expect that a center frequency for a downlink BWP is the same as a center frequency for an uplink BWP.

For a downlink BWP in a set of configured downlink BWPs on a primary cell (PCell), a base station may configure a UE with one or more control resource sets (CORESETs) for at least one search space. A search space is a set of locations in the time and frequency domains where the UE may find control information. The search space may be a UE-specific search space or a common search space (potentially usable by a plurality of UEs). For example, a base station may configure a UE with a common search space, on a PCell or on a primary secondary cell (PSCell), in an active downlink BWP.

For an uplink BWP in a set of configured uplink BWPs, a BS may configure a UE with one or more resource sets for one or more PUCCH transmissions. A UE may receive downlink receptions (e.g., PDCCH or PDSCH) in a downlink BWP according to a configured numerology (e.g., subcarrier spacing and cyclic prefix duration) for the downlink BWP. The UE may transmit uplink transmissions (e.g., PUCCH or PUSCH) in an uplink BWP according to a configured numerology (e.g., subcarrier spacing and cyclic prefix length for the uplink BWP).

One or more BWP indicator fields may be provided in Downlink Control Information (DCI). A value of a BWP indicator field may indicate which BWP in a set of configured BWPs is an active downlink BWP for one or more downlink receptions. The value of the one or more BWP indicator fields may indicate an active uplink BWP for one or more uplink transmissions.

A base station may semi-statically configure a UE with a default downlink BWP within a set of configured downlink BWPs associated with a PCell. If the base station does not provide the default downlink BWP to the UE, the default downlink BWP may be an initial active downlink BWP. The UE may determine which BWP is the initial active downlink BWP based on a CORESET configuration obtained using the PBCH.

A base station may configure a UE with a BWP inactivity timer value for a PCell. The UE may start or restart a BWP inactivity timer at any appropriate time. For example, the UE may start or restart the BWP inactivity timer (a) when the UE detects a DCI indicating an active downlink BWP other than a default downlink BWP for a paired spectra operation; or (b) when a UE detects a DCI indicating an active downlink BWP or active uplink BWP other than a default downlink BWP or uplink BWP for an unpaired spectra operation. If the UE does not detect DCI during an interval of time (e.g., 1 ms or 0.5 ms), the UE may run the BWP inactivity timer toward expiration (for example, increment from zero to the BWP inactivity timer value, or decrement from the BWP inactivity timer value to zero). When the BWP inactivity timer expires, the UE may switch from the active downlink BWP to the default downlink BWP.

In an example, a base station may semi-statically configure a UE with one or more BWPs. A UE may switch an active BWP from a first BWP to a second BWP in response to receiving a DCI indicating the second BWP as an active BWP and/or in response to an expiry of the BWP inactivity timer (e.g., if the second BWP is the default BWP).

Downlink and uplink BWP switching (where BWP switching refers to switching from a currently active BWP to a not currently active BWP) may be performed independently in paired spectra. In unpaired spectra, downlink and uplink BWP switching may be performed simultaneously. Switching between configured BWPs may occur based on RRC signaling, DCI, expiration of a BWP inactivity timer, and/or an initiation of random access.

FIG. **9** illustrates an example of bandwidth adaptation using three configured BWPs for an NR carrier. A UE configured with the three BWPs may switch from one BWP to another BWP at a switching point. In the example illustrated in FIG. **9**, the BWPs include: a BWP **902** with a bandwidth of 40 MHz and a subcarrier spacing of 15 kHz; a BWP **904** with a bandwidth of 10 MHz and a subcarrier spacing of 15 kHz; and a BWP **906** with a bandwidth of 20 MHz and a subcarrier spacing of 60 kHz. The BWP **902** may be an initial active BWP, and the BWP **904** may be a default BWP. The UE may switch between BWPs at switching points. In the example of FIG. **9**, the UE may switch from the BWP **902** to the BWP **904** at a switching point **908**. The switching at the switching point **908** may occur for any suitable reason, for example, in response to an expiry of a BWP inactivity timer (indicating switching to the default BWP) and/or in response to receiving a DCI indicating BWP **904** as the active BWP. The UE may switch at a switching point **910** from active BWP **904** to BWP **906** in response receiving a DCI indicating BWP **906** as the active BWP. The UE may switch at a switching point **912** from active BWP **906** to BWP **904** in response to an expiry of a BWP inactivity timer and/or in response receiving a DCI indicating BWP **904** as the active BWP. The UE may switch at a switching point **914** from active BWP **904** to BWP **902** in response receiving a DCI indicating BWP **902** as the active BWP.

If a UE is configured for a secondary cell with a default downlink BWP in a set of configured downlink BWPs and a timer value, UE procedures for switching BWPs on a secondary cell may be the same/similar as those on a primary cell. For example, the UE may use the timer value and the default downlink BWP for the secondary cell in the same/similar manner as the UE would use these values for a primary cell.

To provide for greater data rates, two or more carriers can be aggregated and simultaneously transmitted to/from the same UE using carrier aggregation (CA). The aggregated carriers in CA may be referred to as component carriers (CCs). When CA is used, there are a number of serving cells for the UE, one for a CC. The CCs may have three configurations in the frequency domain.

FIG. **10**A illustrates the three CA configurations with two CCs. In the intraband, contiguous configuration **1002**, the two CCs are aggregated in the same frequency band (frequency band A) and are located directly adjacent to each other within the frequency band. In the intraband, non-contiguous configuration **1004**, the two CCs are aggregated in the same frequency band (frequency band A) and are separated in the frequency band by a gap. In the interband configuration **1006**, the two CCs are located in frequency bands (frequency band A and frequency band B).

In an example, up to 32 CCs may be aggregated. The aggregated CCs may have the same or different bandwidths, subcarrier spacing, and/or duplexing schemes (TDD or FDD). A serving cell for a UE using CA may have a downlink CC. For FDD, one or more uplink CCs may be optionally configured for a serving cell. The ability to aggregate more downlink carriers than uplink carriers may be useful, for example, when the UE has more data traffic in the downlink than in the uplink.

When CA is used, one of the aggregated cells for a UE may be referred to as a primary cell (PCell). The PCell may be the serving cell that the UE initially connects to at RRC connection establishment, reestablishment, and/or handover. The PCell may provide the UE with NAS mobility information and the security input. UEs may have different PCells. In the downlink, the carrier corresponding to the PCell may be referred to as the downlink primary CC (DL PCC). In the uplink, the carrier corresponding to the PCell may be referred to as the uplink primary CC (UL PCC). The other aggregated cells for the UE may be referred to as secondary cells (SCells). In an example, the SCells may be configured after the PCell is configured for the UE. For example, an SCell may be configured through an RRC Connection Reconfiguration procedure. In the downlink, the carrier corresponding to an SCell may be referred to as a downlink secondary CC (DL SCC). In the uplink, the carrier corresponding to the SCell may be referred to as the uplink secondary CC (UL SCC).

Configured SCells for a UE may be activated and deactivated based on, for example, traffic and channel conditions. Deactivation of an SCell may mean that PDCCH and PDSCH reception on the SCell is stopped and PUSCH, SRS, and CQI transmissions on the SCell are stopped. Configured SCells may be activated and deactivated using a MAC CE with respect to FIG. **4**B. For example, a MAC CE may use a bitmap (e.g., one bit per SCell) to indicate which SCells (e.g., in a subset of configured SCells) for the UE are activated or deactivated. Configured SCells may be deactivated in response to an expiration of an SCell deactivation timer (e.g., one SCell deactivation timer per SCell).

Downlink control information, such as scheduling assignments and scheduling grants, for a cell may be transmitted on the cell corresponding to the assignments and grants, which is known as self-scheduling. The DCI for the cell may be transmitted on another cell, which is known as cross-carrier scheduling. Uplink control information (e.g., HARQ acknowledgments and channel state feedback, such as CQI, PMI, and/or RI) for aggregated cells may be transmitted on the PUCCH of the PCell. For a larger number of aggregated downlink CCs, the PUCCH of the PCell may become overloaded. Cells may be divided into multiple PUCCH groups.

FIG. **10**B illustrates an example of how aggregated cells may be configured into one or more PUCCH groups. A PUCCH group **1010** and a PUCCH group **1050** may include one or more downlink CCs, respectively. In the example of FIG. **10**B, the PUCCH group **1010** includes three downlink CCs: a PCell **1011**, an SCell **1012**, and an SCell **1013**. The PUCCH group **1050** includes three downlink CCs in the present example: a PCell **1051**, an SCell **1052**, and an SCell **1053**. One or more uplink CCs may be configured as a PCell **1021**, an SCell **1022**, and an SCell **1023**. One or more other uplink CCs may be configured as a primary SCell (PSCell) **1061**, an SCell **1062**, and an SCell **1063**. Uplink control information (UCI) related to the downlink CCs of the PUCCH group **1010**, shown as UCI **1031**, UCI **1032**, and UCI **1033**, may be transmitted in the uplink of the PCell **1021**. Uplink control information (UCI) related to the downlink CCs of the PUCCH group **1050**, shown as UCI **1071**, UCI **1072**, and UCI **1073**, may be transmitted in the uplink of the PSCell **1061**. In an example, if the aggregated cells depicted in FIG. **10**B were not divided into the PUCCH group **1010** and the PUCCH group **1050**, a single uplink PCell to transmit UCI relating to the downlink CCs, and the PCell may become overloaded. By dividing transmissions of UCI between the PCell **1021** and the PSCell **1061**, overloading may be prevented.

A cell, comprising a downlink carrier and optionally an uplink carrier, may be assigned with a physical cell ID and a cell index. The physical cell ID or the cell index may identify a downlink carrier and/or an uplink carrier of the cell, for example, depending on the context in which the physical cell ID is used. A physical cell ID may be determined using a synchronization signal transmitted on a downlink component carrier. A cell index may be determined using RRC messages. In the disclosure, a physical cell ID may be referred to as a carrier ID, and a cell index may be referred to as a carrier index. For example, when the disclosure refers to a first physical cell ID for a first downlink carrier, the disclosure may mean the first physical cell ID is for a cell comprising the first downlink carrier. The same/similar concept may apply to, for example, a carrier activation. When the disclosure indicates that a first carrier is activated, the specification may mean that a cell comprising the first carrier is activated.

In CA, a multi-carrier nature of a PHY may be exposed to a MAC. In an example, a HARQ entity may operate on a serving cell. A transport block may be generated per assignment/grant per serving cell. A transport block and potential HARQ retransmissions of the transport block may be mapped to a serving cell.

In the downlink, a base station may transmit (e.g., unicast, multicast, and/or broadcast) one or more Reference Signals (RSs) to a UE (e.g., PSS, SSS, CSI-RS, DMRS, and/or PT-RS, as shown in FIG. **5**A). In the uplink, the UE may transmit one or more RSs to the base station (e.g., DMRS, PT-RS, and/or SRS, as shown in FIG. **5**B). The PSS and the SSS may be transmitted by the base station and used by the UE to synchronize the UE to the base station. The PSS and the SSS may be provided in a synchronization signal (SS)/physical broadcast channel (PBCH) block that includes the PSS, the SSS, and the PBCH. The base station may periodically transmit a burst of SS/PBCH blocks.

FIG. 11A illustrates an example of an SS/PBCH block's structure and location. A burst of SS/PBCH blocks may include one or more SS/PBCH blocks (e.g., 4 SS/PBCH blocks, as shown in FIG. 11A). Bursts may be transmitted periodically (e.g., every 2 frames or 20 ms). A burst may be restricted to a half-frame (e.g., a first half-frame having a duration of 5 ms). It will be understood that FIG. 11A is an example, and that these parameters (number of SS/PBCH blocks per burst, periodicity of bursts, position of burst within the frame) may be configured based on, for example: a carrier frequency of a cell in which the SS/PBCH block is transmitted; a numerology or subcarrier spacing of the cell; a configuration by the network (e.g., using RRC signaling); or any other suitable factor. In an example, the UE may assume a subcarrier spacing for the SS/PBCH block based on the carrier frequency being monitored, unless the radio network configured the UE to assume a different subcarrier spacing.

The SS/PBCH block may span one or more OFDM symbols in the time domain (e.g., 4 OFDM symbols, as shown in the example of FIG. 11A) and may span one or more subcarriers in the frequency domain (e.g., 240 contiguous subcarriers). The PSS, the SSS, and the PBCH may have a common center frequency. The PSS may be transmitted first and may span, for example, 1 OFDM symbol and 127 subcarriers. The SSS may be transmitted after the PSS (e.g., two symbols later) and may span 1 OFDM symbol and 127 subcarriers. The PBCH may be transmitted after the PSS (e.g., across the next 3 OFDM symbols) and may span 240 subcarriers.

The location of the SS/PBCH block in the time and frequency domains may not be known to the UE (e.g., if the UE is searching for the cell). To find and select the cell, the UE may monitor a carrier for the PSS. For example, the UE may monitor a frequency location within the carrier. If the PSS is not found after a certain duration (e.g., 20 ms), the UE may search for the PSS at a different frequency location within the carrier, as indicated by a synchronization raster. If the PSS is found at a location in the time and frequency domains, the UE may determine, based on a known structure of the SS/PBCH block, the locations of the SSS and the PBCH, respectively. The SS/PBCH block may be a cell-defining SS block (CD-SSB). In an example, a primary cell may be associated with a CD-SSB. The CD-SSB may be located on a synchronization raster. In an example, a cell selection/search and/or reselection may be based on the CD-SSB.

The SS/PBCH block may be used by the UE to determine one or more parameters of the cell. For example, the UE may determine a physical cell identifier (PCI) of the cell based on the sequences of the PSS and the SSS, respectively. The UE may determine a location of a frame boundary of the cell based on the location of the SS/PBCH block. For example, the SS/PBCH block may indicate that it has been transmitted in accordance with a transmission pattern, wherein a SS/PBCH block in the transmission pattern is a known distance from the frame boundary.

The PBCH may use a QPSK modulation and may use forward error correction (FEC). The FEC may use polar coding. One or more symbols spanned by the PBCH may carry one or more DMRSs for demodulation of the PBCH. The PBCH may include an indication of a current system frame number (SFN) of the cell and/or a SS/PBCH block timing index. These parameters may facilitate time synchronization of the UE to the base station. The PBCH may include a master information block (MIB) used to provide the UE with one or more parameters. The MIB may be used by the UE to locate remaining minimum system information (RMSI) associated with the cell. The RMSI may include a System Information Block Type 1 (SIB1). The SIB1 may contain information needed by the UE to access the cell. The UE may use one or more parameters of the MIB to monitor PDCCH, which may be used to schedule PDSCH. The PDSCH may include the SIB1. The SIB1 may be decoded using parameters provided in the MIB. The PBCH may indicate an absence of SIB1. Based on the PBCH indicating the absence of SIB1, the UE may be pointed to a frequency. The UE may search for an SS/PBCH block at the frequency to which the UE is pointed.

The UE may assume that one or more SS/PBCH blocks transmitted with a same SS/PBCH block index are quasi co-located (QCLed) (e.g., having the same/similar Doppler spread, Doppler shift, average gain, average delay, and/or spatial Rx parameters). The UE may not assume QCL for SS/PBCH block transmissions having different SS/PBCH block indices.

SS/PBCH blocks (e.g., those within a half-frame) may be transmitted in spatial directions (e.g., using different beams that span a coverage area of the cell). In an example, a first SS/PBCH block may be transmitted in a first spatial direction using a first beam, and a second SS/PBCH block may be transmitted in a second spatial direction using a second beam.

In an example, within a frequency span of a carrier, a base station may transmit a plurality of SS/PBCH blocks. In an example, a first PCI of a first SS/PBCH block of the plurality of SS/PBCH blocks may be different from a second PCI of a second SS/PBCH block of the plurality of SS/PBCH blocks. The PCIs of SS/PBCH blocks transmitted in different frequency locations may be different or the same.

The CSI-RS may be transmitted by the base station and used by the UE to acquire channel state information (CSI). The base station may configure the UE with one or more CSI-RSs for channel estimation or any other suitable purpose. The base station may configure a UE with one or more of the same/similar CSI-RSs. The UE may measure the one or more CSI-RSs. The UE may estimate a downlink channel state and/or generate a CSI report based on the measuring of the one or more downlink CSI-RSs. The UE may provide the CSI report to the base station. The base station may use feedback provided by the UE (e.g., the estimated downlink channel state) to perform link adaptation.

The base station may semi-statically configure the UE with one or more CSI-RS resource sets. A CSI-RS resource may be associated with a location in the time and frequency domains and a periodicity. The base station may selectively activate and/or deactivate a CSI-RS resource. The base station may indicate to the UE that a CSI-RS resource in the CSI-RS resource set is activated and/or deactivated.

The base station may configure the UE to report CSI measurements. The base station may configure the UE to provide CSI reports periodically, aperiodically, or semi-persistently. For periodic CSI reporting, the UE may be configured with a timing and/or periodicity of a plurality of CSI reports. For aperiodic CSI reporting, the base station may request a CSI report. For example, the base station may command the UE to measure a configured CSI-RS resource and provide a CSI report relating to the measurements. For semi-persistent CSI reporting, the base station may configure the UE to transmit periodically, and selectively activate or deactivate the periodic reporting. The base station may configure the UE with a CSI-RS resource set and CSI reports using RRC signaling.

The CSI-RS configuration may comprise one or more parameters indicating, for example, up to 32 antenna ports. The UE may be configured to employ the same OFDM symbols for a downlink CSI-RS and a control resource set (CORESET) when the downlink CSI-RS and CORESET are spatially QCLed and resource elements associated with the downlink CSI-RS are outside of the physical resource blocks (PRBs) configured for the CORESET. The UE may be configured to employ the same OFDM symbols for downlink CSI-RS and SS/PBCH blocks when the downlink CSI-RS and SS/PBCH blocks are spatially QCLed and resource elements associated with the downlink CSI-RS are outside of PRBs configured for the SS/PBCH blocks.

Downlink DMRSs may be transmitted by a base station and used by a UE for channel estimation. For example, the downlink DMRS may be used for coherent demodulation of one or more downlink physical channels (e.g., PDSCH). An NR network may support one or more variable and/or configurable DMRS patterns for data demodulation. At least one downlink DMRS configuration may support a front-loaded DMRS pattern. A front-loaded DMRS may be mapped over one or more OFDM symbols (e.g., one or two adjacent OFDM symbols). A base station may semi-statically configure the UE with a number (e.g. a maximum number) of front-loaded DMRS symbols for PDSCH. A DMRS configuration may support one or more DMRS ports. For example, for single user-MIMO, a DMRS configuration may support up to eight orthogonal downlink DMRS ports per UE. For multiuser-MIMO, a DMRS configuration may support up to 4 orthogonal downlink DMRS ports per UE. A radio network may support (e.g., at least for CP-OFDM) a common DMRS structure for downlink and uplink, wherein a DMRS location, a DMRS pattern, and/or a scrambling sequence may be the same or different. The base station may transmit a downlink DMRS and a corresponding PDSCH using the same precoding matrix. The UE may use the one or more downlink DMRSs for coherent demodulation/channel estimation of the PDSCH.

In an example, a transmitter (e.g., a base station) may use a precoder matrices for a part of a transmission bandwidth. For example, the transmitter may use a first precoder matrix for a first bandwidth and a second precoder matrix for a second bandwidth. The first precoder matrix and the second precoder matrix may be different based on the first bandwidth being different from the second bandwidth. The UE may assume that a same precoding matrix is used across a set of PRBs. The set of PRBs may be denoted as a precoding resource block group (PRG).

A PDSCH may comprise one or more layers. The UE may assume that at least one symbol with DMRS is present on a layer of the one or more layers of the PDSCH. A higher layer may configure up to 3 DMRSs for the PDSCH.

Downlink PT-RS may be transmitted by a base station and used by a UE for phase-noise compensation. Whether a downlink PT-RS is present or not may depend on an RRC configuration. The presence and/or pattern of the downlink PT-RS may be configured on a UE-specific basis using a combination of RRC signaling and/or an association with one or more parameters employed for other purposes (e.g., modulation and coding scheme (MCS)), which may be indicated by DCI. When configured, a dynamic presence of a downlink PT-RS may be associated with one or more DCI parameters comprising at least MCS. An NR network may support a plurality of PT-RS densities defined in the time and/or frequency domains. When present, a frequency domain density may be associated with at least one configuration of a scheduled bandwidth. The UE may assume a same precoding for a DMRS port and a PT-RS port. A number of PT-RS ports may be fewer than a number of DMRS ports in a scheduled resource. Downlink PT-RS may be confined in the scheduled time/frequency duration for the UE. Downlink PT-RS may be transmitted on symbols to facilitate phase tracking at the receiver.

The UE may transmit an uplink DMRS to a base station for channel estimation. For example, the base station may use the uplink DMRS for coherent demodulation of one or more uplink physical channels. For example, the UE may transmit an uplink DMRS with a PUSCH and/or a PUCCH. The uplink DM-RS may span a range of frequencies that is similar to a range of frequencies associated with the corresponding physical channel. The base station may configure the UE with one or more uplink DMRS configurations. At least one DMRS configuration may support a front-loaded DMRS pattern. The front-loaded DMRS may be mapped over one or more OFDM symbols (e.g., one or two adjacent OFDM symbols). One or more uplink DMRSs may be configured to transmit at one or more symbols of a PUSCH and/or a PUCCH. The base station may semi-statically configure the UE with a number (e.g. maximum number) of front-loaded DMRS symbols for the PUSCH and/or the PUCCH, which the UE may use to schedule a single-symbol DMRS and/or a double-symbol DMRS. An NR network may support (e.g., for cyclic prefix orthogonal frequency division multiplexing (CP-OFDM)) a common DMRS structure for downlink and uplink, wherein a DMRS location, a DMRS pattern, and/or a scrambling sequence for the DMRS may be the same or different.

A PUSCH may comprise one or more layers, and the UE may transmit at least one symbol with DMRS present on a layer of the one or more layers of the PUSCH. In an example, a higher layer may configure up to three DMRSs for the PUSCH.

Uplink PT-RS (which may be used by a base station for phase tracking and/or phase-noise compensation) may or may not be present depending on an RRC configuration of the UE. The presence and/or pattern of uplink PT-RS may be configured on a UE-specific basis by a combination of RRC signaling and/or one or more parameters employed for other purposes (e.g., Modulation and Coding Scheme (MCS)), which may be indicated by DCI. When configured, a dynamic presence of uplink PT-RS may be associated with one or more DCI parameters comprising at least MCS. A radio network may support a plurality of uplink PT-RS densities defined in time/frequency domain. When present, a frequency domain density may be associated with at least one configuration of a scheduled bandwidth. The UE may assume a same precoding for a DMRS port and a PT-RS port. A number of PT-RS ports may be fewer than a number of DMRS ports in a scheduled resource. For example, uplink PT-RS may be confined in the scheduled time/frequency duration for the UE.

SRS may be transmitted by a UE to a base station for channel state estimation to support uplink channel dependent scheduling and/or link adaptation. SRS transmitted by the UE may allow a base station to estimate an uplink channel state at one or more frequencies. A scheduler at the base station may employ the estimated uplink channel state to assign one or more resource blocks for an uplink PUSCH transmission from the UE. The base station may semi-statically configure the UE with one or more SRS resource sets. For an SRS resource set, the base station may configure the UE with one or more SRS resources. An SRS resource set applicability may be configured by a higher layer (e.g., RRC) parameter. For example, when a higher layer parameter indicates beam management, an SRS resource in a SRS resource set of the one or more SRS resource sets (e.g., with the same/similar time domain behavior, periodic, aperiodic, and/or the like) may be transmitted at a time instant (e.g., simultaneously). The UE may transmit one or more SRS resources in SRS resource sets. An NR network may support aperiodic, periodic and/or semi-persistent SRS transmissions. The UE may transmit SRS resources based on one or more trigger types, wherein the one or more trigger types may comprise higher layer signaling (e.g., RRC) and/or one or more DCI formats. In an example, at least one DCI format may be employed for the UE to select at least one of one or more configured SRS resource sets. An SRS trigger type 0 may refer to an SRS triggered based on a higher layer signaling. An SRS trigger type 1 may refer to an SRS triggered based on one or more DCI formats. In an example, when PUSCH and SRS are transmitted in a same slot, the UE may be configured to transmit SRS after a transmission of a PUSCH and a corresponding uplink DMRS.

The base station may semi-statically configure the UE with one or more SRS configuration parameters indicating at least one of following: a SRS resource configuration identifier; a number of SRS ports; time domain behavior of an SRS resource configuration (e.g., an indication of periodic, semi-persistent, or aperiodic SRS); slot, mini-slot, and/or subframe level periodicity; offset for a periodic and/or an aperiodic SRS resource; a number of OFDM symbols in an SRS resource; a starting OFDM symbol of an SRS resource; an SRS bandwidth; a frequency hopping bandwidth; a cyclic shift; and/or an SRS sequence ID.

An antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed. If a first symbol and a second symbol are transmitted on the same antenna port, the receiver may infer the channel (e.g., fading gain, multipath delay, and/or the like) for conveying the second symbol on the antenna port, from the channel for conveying the first symbol on the antenna port. A first antenna port and a second antenna port may be referred to as quasi co-located (QCLed) if one or more large-scale properties of the channel over which a first symbol on the first antenna port is conveyed may be inferred from the channel over which a second symbol on a second antenna port is conveyed. The one or more large-scale properties may comprise at least one of: a delay spread; a Doppler spread; a Doppler shift; an average gain; an average delay; and/or spatial Receiving (Rx) parameters.

Channels that use beamforming require beam management. Beam management may comprise beam measurement, beam selection, and beam indication. A beam may be associated with one or more reference signals. For example, a beam may be identified by one or more beamformed reference signals. The UE may perform downlink beam measurement based on downlink reference signals (e.g., a channel state information reference signal (CSI-RS)) and generate a beam measurement report. The UE may perform the downlink beam measurement procedure after an RRC connection is set up with a base station.

FIG. **11**B illustrates an example of channel state information reference signals (CSI-RSs) that are mapped in the time and frequency domains. A square shown in FIG. **11**B may span a resource block (RB) within a bandwidth of a cell. A base station may transmit one or more RRC messages comprising CSI-RS resource configuration parameters indicating one or more CSI-RSs. One or more of the following parameters may be configured by higher layer signaling (e.g., RRC and/or MAC signaling) for a CSI-RS resource configuration: a CSI-RS resource configuration identity, a number of CSI-RS ports, a CSI-RS configuration (e.g., symbol and resource element (RE) locations in a subframe), a CSI-RS subframe configuration (e.g., subframe location, offset, and periodicity in a radio frame), a CSI-RS power parameter, a CSI-RS sequence parameter, a code division multiplexing (CDM) type parameter, a frequency density, a transmission comb, quasi co-location (QCL) parameters (e.g., QCL-scramblingidentity, crs-portscount, mbsfn-subframeconfiglist, csi-rs-configZPid, qcl-csi-rs-configNZPid), and/or other radio resource parameters.

The three beams illustrated in FIG. **11**B may be configured for a UE in a UE-specific configuration. Three beams are illustrated in FIG. **11**B (beam #1, beam #2, and beam #3), more or fewer beams may be configured. Beam #1 may be allocated with CSI-RS **1101** that may be transmitted in one or more subcarriers in an RB of a first symbol. Beam #2 may be allocated with CSI-RS **1102** that may be transmitted in one or more subcarriers in an RB of a second symbol. Beam #3 may be allocated with CSI-RS **1103** that may be transmitted in one or more subcarriers in an RB of a third symbol. By using frequency division multiplexing (FDM), a base station may use other subcarriers in a same RB (for example, those that are not used to transmit CSI-RS **1101**) to transmit another CSI-RS associated with a beam for another UE. By using time domain multiplexing (TDM), beams used for the UE may be configured such that beams for the UE use symbols from beams of other UEs.

CSI-RSs such as those illustrated in FIG. **11**B (e.g., CSI-RS **1101**, **1102**, **1103**) may be transmitted by the base station and used by the UE for one or more measurements. For example, the UE may measure a reference signal received power (RSRP) of configured CSI-RS resources. The base station may configure the UE with a reporting configuration and the UE may report the RSRP measurements to a network (for example, via one or more base stations) based on the reporting configuration. In an example, the base station may determine, based on the reported measurement results, one or more transmission configuration indication (TCI) states comprising a number of reference signals. In an example, the base station may indicate one or more TCI states to the UE (e.g., via RRC signaling, a MAC CE, and/or a DCI). The UE may receive a downlink transmission with a receive (Rx) beam determined based on the one or more TCI states. In an example, the UE may or may not have a capability of beam correspondence. If the UE has the capability of beam correspondence, the UE may determine a spatial domain filter of a transmit (Tx) beam based on a spatial domain filter of the corresponding Rx beam. If the UE does not have the capability of beam correspondence, the UE may perform an uplink beam selection procedure to determine the spatial domain filter of the Tx beam. The UE may perform the uplink beam selection procedure based on one or more sounding reference signal (SRS) resources configured to the UE by the base station. The base station may select and indicate uplink beams for the UE based on measurements of the one or more SRS resources transmitted by the UE.

In a beam management procedure, a UE may assess (e.g., measure) a channel quality of one or more beam pair links, a beam pair link comprising a transmitting beam transmitted by a base station and a receiving beam received by the UE. Based on the assessment, the UE may transmit a beam measurement report indicating one or more beam pair quality parameters comprising, e.g., one or more beam identifications (e.g., a beam index, a reference signal index, or the like), RSRP, a precoding matrix indicator (PMI), a channel quality indicator (CQI), and/or a rank indicator (RI).

FIG. **12**A illustrates examples of three downlink beam management procedures: P**1**, P**2**, and P**3**. Procedure P**1** may enable a UE measurement on transmit (Tx) beams of a transmission reception point (TRP) (or multiple TRPs), e.g., to support a selection of one or more base station Tx beams and/or UE Rx beams (shown as ovals in the top row and bottom row, respectively, of P**1**). Beamforming at a TRP may comprise a Tx beam sweep for a set of beams (shown, in the top rows of P**1** and P**2**, as ovals rotated in a counter-clockwise direction indicated by the dashed arrow). Beamforming at a UE may comprise an Rx beam sweep for a set of beams (shown, in the bottom rows of P**1** and P**3**, as ovals rotated in a clockwise direction indicated by the dashed arrow). Procedure P**2** may be used to enable a UE measurement on Tx beams of a TRP (shown, in the top row of P**2**, as ovals rotated in a counter-clockwise direction indicated by the dashed arrow). The UE and/or the base station may perform procedure P**2** using a smaller set of beams than is used in procedure P**1**, or using narrower beams than the beams used in procedure P**1**. This may be referred to as beam refinement. The UE may perform procedure P**3** for Rx beam determination by using the same Tx beam at the base station and sweeping an Rx beam at the UE.

FIG. **12**B illustrates examples of three uplink beam management procedures: U**1**, U**2**, and U**3**. Procedure U**1** may be used to enable a base station to perform a measurement on Tx beams of a UE, e.g., to support a selection of one or more UE Tx beams and/or base station Rx beams (shown as ovals in the top row and bottom row, respectively, of U**1**). Beamforming at the UE may include, e.g., a Tx beam sweep from a set of beams (shown in the bottom rows of U**1** and U**3** as ovals rotated in a clockwise direction indicated by the dashed arrow). Beamforming at the base station may include, e.g., an Rx beam sweep from a set of beams (shown, in the top rows of U**1** and U**2**, as ovals rotated in a counter-clockwise direction indicated by the dashed arrow). Procedure U**2** may be used to enable the base station to adjust its Rx beam when the UE uses a fixed Tx beam. The UE and/or the base station may perform procedure U**2** using a smaller set of beams than is used in procedure P**1**, or using narrower beams than the beams used in procedure P**1**. This may be referred to as beam refinement The UE may perform procedure U**3** to adjust its Tx beam when the base station uses a fixed Rx beam.

A UE may initiate a beam failure recovery (BFR) procedure based on detecting a beam failure. The UE may transmit a BFR request (e.g., a preamble, a UCI, an SR, a MAC CE, and/or the like) based on the initiating of the BFR procedure. The UE may detect the beam failure based on a determination that a quality of beam pair link(s) of an associated control channel is unsatisfactory (e.g., having an error rate higher than an error rate threshold, a received signal power lower than a received signal power threshold, an expiration of a timer, and/or the like).

The UE may measure a quality of a beam pair link using one or more reference signals (RSs) comprising one or more SS/PBCH blocks, one or more CSI-RS resources, and/or one or more demodulation reference signals (DMRSs). A quality of the beam pair link may be based on one or more of a block error rate (BLER), an RSRP value, a signal to interference plus noise ratio (SINR) value, a reference signal received quality (RSRQ) value, and/or a CSI value measured on RS resources. The base station may indicate that an RS resource is quasi co-located (QCLed) with one or more DM-RSs of a channel (e.g., a control channel, a shared data channel, and/or the like). The RS resource and the one or more DMRSs of the channel may be QCLed when the channel characteristics (e.g., Doppler shift, Doppler spread, average delay, delay spread, spatial Rx parameter, fading, and/or the like) from a transmission via the RS resource to the UE are similar or the same as the channel characteristics from a transmission via the channel to the UE.

A network (e.g., a gNB and/or an ng-eNB of a network) and/or the UE may initiate a random access procedure. A UE in an RRC_IDLE state and/or an RRC_INACTIVE state may initiate the random access procedure to request a connection setup to a network. The UE may initiate the random access procedure from an RRC_CONNECTED state. The UE may initiate the random access procedure to request uplink resources (e.g., for uplink transmission of an SR when there is no PUCCH resource available) and/or acquire uplink timing (e.g., when uplink synchronization status is non-synchronized). The UE may initiate the random access procedure to request one or more system information blocks (SIBs) (e.g., other system information such as SIB2, SIB3, and/or the like). The UE may initiate the random access procedure for a beam failure recovery request. A network may initiate a random access procedure for a handover and/or for establishing time alignment for an SCell addition.

FIG. **13**A illustrates a four-step contention-based random access procedure. Prior to initiation of the procedure, a base station may transmit a configuration message **1310** to the UE. The procedure illustrated in FIG. **13**A comprises transmission of four messages: a Msg 1 **1311**, a Msg 2 **1312**, a Msg 3 **1313**, and a Msg 4 **1314**. The Msg 1 **1311** may include and/or be referred to as a preamble (or a random access preamble). The Msg 2 **1312** may include and/or be referred to as a random access response (RAR).

The configuration message **1310** may be transmitted, for example, using one or more RRC messages. The one or more RRC messages may indicate one or more random access channel (RACH) parameters to the UE. The one or more RACH parameters may comprise at least one of following: general parameters for one or more random access procedures (e.g., RACH-configGeneral); cell-specific parameters (e.g., RACH-ConfigCommon); and/or dedicated parameters (e.g., RACH-configDedicated). The base station may broadcast or multicast the one or more RRC messages to one or more UEs. The one or more RRC messages may be UE-specific (e.g., dedicated RRC messages transmitted to a UE in an RRC_CONNECTED state and/or in an RRC_INACTIVE state). The UE may determine, based on the one or more RACH parameters, a time-frequency resource and/or an uplink transmit power for transmission of the Msg 1 **1311** and/or the Msg 3 **1313**. Based on the one or more RACH parameters, the UE may determine a reception timing and a downlink channel for receiving the Msg 2 **1312** and the Msg 4 **1314**.

The one or more RACH parameters provided in the configuration message **1310** may indicate one or more Physical RACH (PRACH) occasions available for transmission of the Msg 1 **1311**. The one or more PRACH occasions may be predefined. The one or more RACH parameters may indicate one or more available sets of one or more PRACH occasions (e.g., prach-ConfigIndex). The one or more RACH parameters may indicate an association between (a) one or more PRACH occasions and (b) one or more reference signals. The one or more RACH parameters may indicate an association between (a) one or more preambles and (b) one or more reference signals. The one or more reference signals may be SS/PBCH blocks and/or CSI-RSs.

For example, the one or more RACH parameters may indicate a number of SS/PBCH blocks mapped to a PRACH occasion and/or a number of preambles mapped to a SS/PBCH blocks.

The one or more RACH parameters provided in the configuration message **1310** may be used to determine an uplink transmit power of Msg 1 **1311** and/or Msg 3 **1313**. For example, the one or more RACH parameters may indicate a reference power for a preamble transmission (e.g., a received target power and/or an initial power of the preamble transmission). There may be one or more power offsets indicated by the one or more RACH parameters. For example, the one or more RACH parameters may indicate: a power ramping step; a power offset between SSB and CSI-RS; a power offset between transmissions of the Msg 1 **1311** and the Msg 3 **1313**; and/or a power offset value between preamble groups. The one or more RACH parameters may indicate one or more thresholds based on which the UE may determine at least one reference signal (e.g., an SSB and/or CSI-RS) and/or an uplink carrier (e.g., a normal uplink (NUL) carrier and/or a supplemental uplink (SUL) carrier).

The Msg 1 **1311** may include one or more preamble transmissions (e.g., a preamble transmission and one or more preamble retransmissions). An RRC message may be used to configure one or more preamble groups (e.g., group A and/or group B). A preamble group may comprise one or more preambles. The UE may determine the preamble group based on a pathloss measurement and/or a size of the Msg 3 **1313**. The UE may measure an RSRP of one or more reference signals (e.g., SSBs and/or CSI-RSs) and determine at least one reference signal having an RSRP above an RSRP threshold (e.g., rsrp-ThresholdSSB and/or rsrp-Threshold-CSI-RS). The UE may select at least one preamble associated with the one or more reference signals and/or a selected preamble group, for example, if the association between the one or more preambles and the at least one reference signal is configured by an RRC message.

The UE may determine the preamble based on the one or more RACH parameters provided in the configuration message **1310**. For example, the UE may determine the preamble based on a pathloss measurement, an RSRP measurement, and/or a size of the Msg 3 **1313**. As another example, the one or more RACH parameters may indicate: a preamble format; a maximum number of preamble transmissions; and/or one or more thresholds for determining one or more preamble groups (e.g., group A and group B). A base station may use the one or more RACH parameters to configure the UE with an association between one or more preambles and one or more reference signals (e.g., SSBs and/or CSI-RSs). If the association is configured, the UE may determine the preamble to include in Msg 1 **1311** based on the association. The Msg 1 **1311** may be transmitted to the base station via one or more PRACH occasions. The UE may use one or more reference signals (e.g., SSBs and/or CSI-RSs) for selection of the preamble and for determining of the PRACH occasion. One or more RACH parameters (e.g., ra-ssb-OccasionMskIndex and/or ra-OccasionList) may indicate an association between the PRACH occasions and the one or more reference signals.

The UE may perform a preamble retransmission if no response is received following a preamble transmission. The UE may increase an uplink transmit power for the preamble retransmission. The UE may select an initial preamble transmit power based on a pathloss measurement and/or a target received preamble power configured by the network. The UE may determine to retransmit a preamble and may ramp up the uplink transmit power. The UE may receive one or more RACH parameters (e.g., PREAMBLE_POWER_RAMPING_STEP) indicating a ramping step for the preamble retransmission. The ramping step may be an amount of incremental increase in uplink transmit power for a retransmission. The UE may ramp up the uplink transmit power if the UE determines a reference signal (e.g., SSB and/or CSI-RS) that is the same as a previous preamble transmission. The UE may count a number of preamble transmissions and/or retransmissions (e.g., PREAMBLE_TRANSMISSION_COUNTER). The UE may determine that a random access procedure completed unsuccessfully, for example, if the number of preamble transmissions exceeds a threshold configured by the one or more RACH parameters (e.g., preambleTransMax).

The Msg 2 **1312** received by the UE may include an RAR. In some scenarios, the Msg 2 **1312** may include multiple RARs corresponding to multiple UEs. The Msg 2 **1312** may be received after or in response to the transmitting of the Msg 1 **1311**. The Msg 2 **1312** may be scheduled on the DL-SCH and indicated on a PDCCH using a random access RNTI (RA-RNTI). The Msg 2 **1312** may indicate that the Msg 1 **1311** was received by the base station. The Msg 2 **1312** may include a time-alignment command that may be used by the UE to adjust the UE's transmission timing, a scheduling grant for transmission of the Msg 3 **1313**, and/or a Temporary Cell RNTI (TC-RNTI). After transmitting a preamble, the UE may start a time window (e.g., ra-ResponseWindow) to monitor a PDCCH for the Msg 2 **1312**. The UE may determine when to start the time window based on a PRACH occasion that the UE uses to transmit the preamble. For example, the UE may start the time window one or more symbols after a last symbol of the preamble (e.g., at a first PDCCH occasion from an end of a preamble transmission). The one or more symbols may be determined based on a numerology. The PDCCH may be in a common search space (e.g., a Type1-PDCCH common search space) configured by an RRC message. The UE may identify the RAR based on a Radio Network Temporary Identifier (RNTI). RNTIs may be used depending on one or more events initiating the random access procedure. The UE may use random access RNTI (RA-RNTI). The RA-RNTI may be associated with PRACH occasions in which the UE transmits a preamble. For example, the UE may determine the RA-RNTI based on: an OFDM symbol index; a slot index; a frequency domain index; and/or a UL carrier indicator of the PRACH occasions. An example of RA-RNTI may be as follows:

$RA\text{-}RNTI=1+s\_id+14\times t\_id+14\times 80\times f\_id+14\times 80\times 8\times ul\_carrier\_id$, where s_id may be an index of a first OFDM symbol of the PRACH occasion (e.g., $0\le s\_id<14$), t_id may be an index of a first slot of the PRACH occasion in a system frame (e.g., $0\le t\_id<80$), f_id may be an index of the PRACH occasion in the frequency domain (e.g., $0\le f\_id<8$), and ul_carrier_id may be a UL carrier used for a preamble transmission (e.g., 0 for an NUL carrier, and 1 for an SUL carrier).

The UE may transmit the Msg 3 **1313** in response to a successful reception of the Msg 2 **1312** (e.g., using resources identified in the Msg 2 **1312**). The Msg 3 **1313** may be used for contention resolution in, for example, the contention-based random access procedure illustrated in FIG. **13**A. In some scenarios, a plurality of UEs may transmit a same preamble to a base station and the base station may provide an RAR that corresponds to a UE. Collisions may occur if the plurality of UEs interpret the RAR as corresponding to themselves. Contention resolution (e.g., using the Msg 3

1313 and the Msg 4 1314) may be used to increase the likelihood that the UE does not incorrectly use an identity of another the UE. To perform contention resolution, the UE may include a device identifier in the Msg 3 1313 (e.g., a C-RNTI if assigned, a TC RNTI included in the Msg 2 1312, and/or any other suitable identifier).

The Msg 4 1314 may be received after or in response to the transmitting of the Msg 3 1313. If a C-RNTI was included in the Msg 3 1313, the base station will address the UE on the PDCCH using the C-RNTI. If the UE's unique C-RNTI is detected on the PDCCH, the random access procedure is determined to be successfully completed. If a TC-RNTI is included in the Msg 3 1313 (e.g., if the UE is in an RRC_IDLE state or not otherwise connected to the base station), Msg 4 1314 will be received using a DL-SCH associated with the TC-RNTI. If a MAC PDU is successfully decoded and a MAC PDU comprises the UE contention resolution identity MAC CE that matches or otherwise corresponds with the CCCH SDU sent (e.g., transmitted) in Msg 3 1313, the UE may determine that the contention resolution is successful and/or the UE may determine that the random access procedure is successfully completed.

The UE may be configured with a supplementary uplink (SUL) carrier and a normal uplink (NUL) carrier. An initial access (e.g., random access procedure) may be supported in an uplink carrier. For example, a base station may configure the UE with two separate RACH configurations: one for an SUL carrier and the other for an NUL carrier. For random access in a cell configured with an SUL carrier, the network may indicate which carrier to use (NUL or SUL). The UE may determine the SUL carrier, for example, if a measured quality of one or more reference signals is lower than a broadcast threshold. Uplink transmissions of the random access procedure (e.g., the Msg 1 1311 and/or the Msg 3 1313) may remain on the selected carrier. The UE may switch an uplink carrier during the random access procedure (e.g., between the Msg 1 1311 and the Msg 3 1313) in one or more cases. For example, the UE may determine and/or switch an uplink carrier for the Msg 1 1311 and/or the Msg 3 1313 based on a channel clear assessment (e.g., a listen-before-talk).

FIG. 13B illustrates a two-step contention-free random access procedure. Similar to the four-step contention-based random access procedure illustrated in FIG. 13A, a base station may, prior to initiation of the procedure, transmit a configuration message 1320 to the UE. The configuration message 1320 may be analogous in some respects to the configuration message 1310. The procedure illustrated in FIG. 13B comprises transmission of two messages: a Msg 1 1321 and a Msg 2 1322. The Msg 1 1321 and the Msg 2 1322 may be analogous in some respects to the Msg 1 1311 and a Msg 2 1312 illustrated in FIG. 13A, respectively. As will be understood from FIGS. 13A and 13B, the contention-free random access procedure may not include messages analogous to the Msg 3 1313 and/or the Msg 4 1314.

The contention-free random access procedure illustrated in FIG. 13B may be initiated for a beam failure recovery, other SI request, SCell addition, and/or handover. For example, a base station may indicate or assign to the UE the preamble to be used for the Msg 1 1321. The UE may receive, from the base station via PDCCH and/or RRC, an indication of a preamble (e.g., ra-PreambleIndex).

After transmitting a preamble, the UE may start a time window (e.g., ra-ResponseWindow) to monitor a PDCCH for the RAR. In the event of a beam failure recovery request, the base station may configure the UE with a separate time window and/or a separate PDCCH in a search space indicated by an RRC message (e.g., recoverySearchSpaceId). The UE may monitor for a PDCCH transmission addressed to a Cell RNTI (C-RNTI) on the search space. In the contention-free random access procedure illustrated in FIG. 13B, the UE may determine that a random access procedure successfully completes after or in response to transmission of Msg 1 1321 and reception of a corresponding Msg 2 1322. The UE may determine that a random access procedure successfully completes, for example, if a PDCCH transmission is addressed to a C-RNTI. The UE may determine that a random access procedure successfully completes, for example, if the UE receives an RAR comprising a preamble identifier corresponding to a preamble transmitted by the UE and/or the RAR comprises a MAC sub-PDU with the preamble identifier. The UE may determine the response as an indication of an acknowledgement for an SI request.

FIG. 13C illustrates another two-step random access procedure. Similar to the random access procedures illustrated in FIGS. 13A and 13B, a base station may, prior to initiation of the procedure, transmit a configuration message 1330 to the UE. The configuration message 1330 may be analogous in some respects to the configuration message 1310 and/or the configuration message 1320. The procedure illustrated in FIG. 13C comprises transmission of two messages: a Msg A 1331 and a Msg B 1332.

Msg A 1331 may be transmitted in an uplink transmission by the UE. Msg A 1331 may comprise one or more transmissions of a preamble 1341 and/or one or more transmissions of a transport block 1342. The transport block 1342 may comprise contents that are similar and/or equivalent to the contents of the Msg 3 1313 illustrated in FIG. 13A. The transport block 1342 may comprise UCI (e.g., an SR, a HARQ ACK/NACK, and/or the like). The UE may receive the Msg B 1332 after or in response to transmitting the Msg A 1331. The Msg B 1332 may comprise contents that are similar and/or equivalent to the contents of the Msg 2 1312 (e.g., an RAR) illustrated in FIGS. 13A and 13B and/or the Msg 4 1314 illustrated in FIG. 13A.

The UE may initiate the two-step random access procedure in FIG. 13C for licensed spectrum and/or unlicensed spectrum. The UE may determine, based on one or more factors, whether to initiate the two-step random access procedure. The one or more factors may be: a radio access technology in use (e.g., LTE, NR, and/or the like); whether the UE has valid TA or not; a cell size; the UE's RRC state; a type of spectrum (e.g., licensed vs. unlicensed); and/or any other suitable factors.

The UE may determine, based on two-step RACH parameters included in the configuration message 1330, a radio resource and/or an uplink transmit power for the preamble 1341 and/or the transport block 1342 included in the Msg A 1331. The RACH parameters may indicate a modulation and coding schemes (MCS), a time-frequency resource, and/or a power control for the preamble 1341 and/or the transport block 1342. A time-frequency resource for transmission of the preamble 1341 (e.g., a PRACH) and a time-frequency resource for transmission of the transport block 1342 (e.g., a PUSCH) may be multiplexed using FDM, TDM, and/or CDM. The RACH parameters may enable the UE to determine a reception timing and a downlink channel for monitoring for and/or receiving Msg B 1332.

The transport block 1342 may comprise data (e.g., delay-sensitive data), an identifier of the UE, security information, and/or device information (e.g., an International Mobile Subscriber Identity (IMSI)). The base station may transmit the Msg B 1332 as a response to the Msg A 1331. The Msg B 1332 may comprise at least one of following: a preamble identifier; a timing advance command; a power control command; an uplink grant (e.g., a radio resource assignment and/or an MCS); a UE identifier for contention resolution; and/or an RNTI (e.g., a C-RNTI or a TC-RNTI). The UE may determine that the two-step random access procedure is successfully completed if: a preamble identifier in the Msg B **1332** is matched to a preamble transmitted by the UE; and/or the identifier of the UE in Msg B **1332** is matched to the identifier of the UE in the Msg A **1331** (e.g., the transport block **1342**).

A UE and a base station may exchange control signaling. The control signaling may be referred to as L1/L2 control signaling and may originate from the PHY layer (e.g., layer 1) and/or the MAC layer (e.g., layer 2). The control signaling may comprise downlink control signaling transmitted from the base station to the UE and/or uplink control signaling transmitted from the UE to the base station.

The downlink control signaling may comprise: a downlink scheduling assignment; an uplink scheduling grant indicating uplink radio resources and/or a transport format; a slot format information; a preemption indication; a power control command; and/or any other suitable signaling. The UE may receive the downlink control signaling in a payload transmitted by the base station on a physical downlink control channel (PDCCH). The payload transmitted on the PDCCH may be referred to as downlink control information (DCI). In some scenarios, the PDCCH may be a group common PDCCH (GC-PDCCH) that is common to a group of UEs.

A base station may attach one or more cyclic redundancy check (CRC) parity bits to a DCI in order to facilitate detection of transmission errors. When the DCI is intended for a UE (or a group of the UEs), the base station may scramble the CRC parity bits with an identifier of the UE (or an identifier of the group of the UEs). Scrambling the CRC parity bits with the identifier may comprise Modulo-2 addition (or an exclusive OR operation) of the identifier value and the CRC parity bits. The identifier may comprise a 16-bit value of a radio network temporary identifier (RNTI).

DCIs may be used for different purposes. A purpose may be indicated by the type of RNTI used to scramble the CRC parity bits. For example, a DCI having CRC parity bits scrambled with a paging RNTI (P-RNTI) may indicate paging information and/or a system information change notification. The P-RNTI may be predefined as "FFFE" in hexadecimal. A DCI having CRC parity bits scrambled with a system information RNTI (SI-RNTI) may indicate a broadcast transmission of the system information. The SI-RNTI may be predefined as "FFFF" in hexadecimal. A DCI having CRC parity bits scrambled with a random access RNTI (RA-RNTI) may indicate a random access response (RAR). A DCI having CRC parity bits scrambled with a cell RNTI (C-RNTI) may indicate a dynamically scheduled unicast transmission and/or a triggering of PDCCH-ordered random access. A DCI having CRC parity bits scrambled with a temporary cell RNTI (TC-RNTI) may indicate a contention resolution (e.g., a Msg 3 analogous to the Msg 3 **1313** illustrated in FIG. **13**A). Other RNTIs configured to the UE by a base station may comprise a Configured Scheduling RNTI (CS-RNTI), a Transmit Power Control-PUCCH RNTI (TPC-PUCCH-RNTI), a Transmit Power Control-PUSCH RNTI (TPC-PUSCH-RNTI), a Transmit Power Control-SRS RNTI (TPC-SRS-RNTI), an Interruption RNTI (INT-RNTI), a Slot Format Indication RNTI (SFI-RNTI), a Semi-Persistent CSI RNTI (SP-CSI-RNTI), a Modulation and Coding Scheme Cell RNTI (MCS-C-RNTI), and/or the like.

Depending on the purpose and/or content of a DCI, the base station may transmit the DCIs with one or more DCI formats. For example, DCI format 0_0 may be used for scheduling of PUSCH in a cell. DCI format 0_0 may be a fallback DCI format (e.g., with compact DCI payloads). DCI format 0_1 may be used for scheduling of PUSCH in a cell (e.g., with more DCI payloads than DCI format 0_0). DCI format 1_0 may be used for scheduling of PDSCH in a cell. DCI format 1_0 may be a fallback DCI format (e.g., with compact DCI payloads). DCI format 1_1 may be used for scheduling of PDSCH in a cell (e.g., with more DCI payloads than DCI format 1_0). DCI format 2_0 may be used for providing a slot format indication to a group of UEs. DCI format 2_1 may be used for notifying a group of UEs of a physical resource block and/or OFDM symbol where the UE may assume no transmission is intended to the UE. DCI format 2_2 may be used for transmission of a transmit power control (TPC) command for PUCCH or PUSCH. DCI format 2_3 may be used for transmission of a group of TPC commands for SRS transmissions by one or more UEs. DCI format(s) for new functions may be defined in future releases. DCI formats may have different DCI sizes, or may share the same DCI size.

After scrambling a DCI with a RNTI, the base station may process the DCI with channel coding (e.g., polar coding), rate matching, scrambling and/or QPSK modulation. A base station may map the coded and modulated DCI on resource elements used and/or configured for a PDCCH. Based on a payload size of the DCI and/or a coverage of the base station, the base station may transmit the DCI via a PDCCH occupying a number of contiguous control channel elements (CCEs). The number of the contiguous CCEs (referred to as aggregation level) may be 1, 2, 4, 8, 16, and/or any other suitable number. A CCE may comprise a number (e.g., 6) of resource-element groups (REGs). A REG may comprise a resource block in an OFDM symbol. The mapping of the coded and modulated DCI on the resource elements may be based on mapping of CCEs and REGs (e.g., CCE-to-REG mapping).

FIG. **14**A illustrates an example of CORESET configurations for a bandwidth part. The base station may transmit a DCI via a PDCCH on one or more control resource sets (CORESETs). A CORESET may comprise a time-frequency resource in which the UE tries to decode a DCI using one or more search spaces. The base station may configure a CORESET in the time-frequency domain. In the example of FIG. **14**A, a first CORESET **1401** and a second CORESET **1402** occur at the first symbol in a slot. The first CORESET **1401** overlaps with the second CORESET **1402** in the frequency domain. A third CORESET **1403** occurs at a third symbol in the slot. A fourth CORESET **1404** occurs at the seventh symbol in the slot. CORESETs may have a different number of resource blocks in frequency domain.

FIG. **14**B illustrates an example of a CCE-to-REG mapping for DCI transmission on a CORESET and PDCCH processing. The CCE-to-REG mapping may be an interleaved mapping (e.g., for the purpose of providing frequency diversity) or a non-interleaved mapping (e.g., for the purposes of facilitating interference coordination and/or frequency-selective transmission of control channels). The base station may perform different or same CCE-to-REG mapping on different CORESETs. A CORESET may be associated with a CCE-to-REG mapping by RRC configuration. A CORESET may be configured with an antenna port quasi co-location (QCL) parameter. The antenna port QCL parameter may indicate QCL information of a demodulation reference signal (DMRS) for PDCCH reception in the CORESET.

The base station may transmit, to the UE, RRC messages comprising configuration parameters of one or more CORESETs and one or more search space sets. The configuration parameters may indicate an association between a search space set and a CORESET. A search space set may comprise a set of PDCCH candidates formed by CCEs at a given aggregation level. The configuration parameters may indicate: a number of PDCCH candidates to be monitored per aggregation level; a PDCCH monitoring periodicity and a PDCCH monitoring pattern; one or more DCI formats to be monitored by the UE; and/or whether a search space set is a common search space set or a UE-specific search space set. A set of CCEs in the common search space set may be predefined and known to the UE. A set of CCEs in the UE-specific search space set may be configured based on the UE's identity (e.g., C-RNTI).

As shown in FIG. **14**B, the UE may determine a time-frequency resource for a CORESET based on RRC messages. The UE may determine a CCE-to-REG mapping (e.g., interleaved or non-interleaved, and/or mapping parameters) for the CORESET based on configuration parameters of the CORESET. The UE may determine a number (e.g., at most 10) of search space sets configured on the CORESET based on the RRC messages. The UE may monitor a set of PDCCH candidates according to configuration parameters of a search space set. The UE may monitor a set of PDCCH candidates in one or more CORESETs for detecting one or more DCIs. Monitoring may comprise decoding one or more PDCCH candidates of the set of the PDCCH candidates according to the monitored DCI formats. Monitoring may comprise decoding a DCI content of one or more PDCCH candidates with possible (or configured) PDCCH locations, possible (or configured) PDCCH formats (e.g., number of CCEs, number of PDCCH candidates in common search spaces, and/or number of PDCCH candidates in the UE-specific search spaces) and possible (or configured) DCI formats. The decoding may be referred to as blind decoding. The UE may determine a DCI as valid for the UE, in response to CRC checking (e.g., scrambled bits for CRC parity bits of the DCI matching a RNTI value). The UE may process information contained in the DCI (e.g., a scheduling assignment, an uplink grant, power control, a slot format indication, a downlink preemption, and/or the like).

The UE may transmit uplink control signaling (e.g., uplink control information (UCI)) to a base station. The uplink control signaling may comprise hybrid automatic repeat request (HARQ) acknowledgements for received DL-SCH transport blocks. The UE may transmit the HARQ acknowledgements after receiving a DL-SCH transport block. Uplink control signaling may comprise channel state information (CSI) indicating channel quality of a physical downlink channel. The UE may transmit the CSI to the base station. The base station, based on the received CSI, may determine transmission format parameters (e.g., comprising multi-antenna and beamforming schemes) for a downlink transmission. Uplink control signaling may comprise scheduling requests (SR). The UE may transmit an SR indicating that uplink data is available for transmission to the base station. The UE may transmit a UCI (e.g., HARQ acknowledgements (HARQ-ACK), CSI report, SR, and the like) via a physical uplink control channel (PUCCH) or a physical uplink shared channel (PUSCH). The UE may transmit the uplink control signaling via a PUCCH using one of several PUCCH formats.

There may be five PUCCH formats and the UE may determine a PUCCH format based on a size of the UCI (e.g., a number of uplink symbols of UCI transmission and a number of UCI bits). PUCCH format 0 may have a length of one or two OFDM symbols and may include two or fewer bits. The UE may transmit UCI in a PUCCH resource using PUCCH format 0 if the transmission is over one or two symbols and the number of HARQ-ACK information bits with positive or negative SR (HARQ-ACK/SR bits) is one or two. PUCCH format 1 may occupy a number between four and fourteen OFDM symbols and may include two or fewer bits. The UE may use PUCCH format 1 if the transmission is four or more symbols and the number of HARQ-ACK/SR bits is one or two. PUCCH format 2 may occupy one or two OFDM symbols and may include more than two bits. The UE may use PUCCH format 2 if the transmission is over one or two symbols and the number of UCI bits is two or more. PUCCH format 3 may occupy a number between four and fourteen OFDM symbols and may include more than two bits. The UE may use PUCCH format 3 if the transmission is four or more symbols, the number of UCI bits is two or more and PUCCH resource does not include an orthogonal cover code. PUCCH format 4 may occupy a number between four and fourteen OFDM symbols and may include more than two bits. The UE may use PUCCH format 4 if the transmission is four or more symbols, the number of UCI bits is two or more and the PUCCH resource includes an orthogonal cover code.

The base station may transmit configuration parameters to the UE for a plurality of PUCCH resource sets using, for example, an RRC message. The plurality of PUCCH resource sets (e.g., up to four sets) may be configured on an uplink BWP of a cell. A PUCCH resource set may be configured with a PUCCH resource set index, a plurality of PUCCH resources with a PUCCH resource being identified by a PUCCH resource identifier (e.g., pucch-Resourceid), and/or a number (e.g. a maximum number) of UCI information bits the UE may transmit using one of the plurality of PUCCH resources in the PUCCH resource set. When configured with a plurality of PUCCH resource sets, the UE may select one of the plurality of PUCCH resource sets based on a total bit length of the UCI information bits (e.g., HARQ-ACK, SR, and/or CSI). If the total bit length of UCI information bits is two or fewer, the UE may select a first PUCCH resource set having a PUCCH resource set index equal to "0". If the total bit length of UCI information bits is greater than two and less than or equal to a first configured value, the UE may select a second PUCCH resource set having a PUCCH resource set index equal to "1". If the total bit length of UCI information bits is greater than the first configured value and less than or equal to a second configured value, the UE may select a third PUCCH resource set having a PUCCH resource set index equal to "2". If the total bit length of UCI information bits is greater than the second configured value and less than or equal to a third value (e.g., 1406), the UE may select a fourth PUCCH resource set having a PUCCH resource set index equal to "3".

After determining a PUCCH resource set from a plurality of PUCCH resource sets, the UE may determine a PUCCH resource from the PUCCH resource set for UCI (HARQ-ACK, CSI, and/or SR) transmission. The UE may determine the PUCCH resource based on a PUCCH resource indicator in a DCI (e.g., with a DCI format 1_0 or DCI for 1_1) received on a PDCCH. A three-bit PUCCH resource indicator in the DCI may indicate one of eight PUCCH resources in the PUCCH resource set. Based on the PUCCH resource indicator, the UE may transmit the UCI (HARQ-ACK, CSI and/or SR) using a PUCCH resource indicated by the PUCCH resource indicator in the DCI.

FIG. **15** illustrates an example of a wireless device **1502** in communication with a base station **1504** in accordance with embodiments of the present disclosure. The wireless device **1502** and base station **1504** may be part of a mobile communication network, such as the mobile communication network **100** illustrated in FIG. **1**A, the mobile communication network **150** illustrated in FIG. **1**B, or any other communication network. Only one wireless device **1502** and one base station **1504** are illustrated in FIG. **15**, but it will be understood that a mobile communication network may include more than one UE and/or more than one base station, with the same or similar configuration as those shown in FIG. **15**.

The base station **1504** may connect the wireless device **1502** to a core network (not shown) through radio communications over the air interface (or radio interface) **1506**. The communication direction from the base station **1504** to the wireless device **1502** over the air interface **1506** is known as the downlink, and the communication direction from the wireless device **1502** to the base station **1504** over the air interface is known as the uplink. Downlink transmissions may be separated from uplink transmissions using FDD, TDD, and/or some combination of the two duplexing techniques.

In the downlink, data to be sent to the wireless device **1502** from the base station **1504** may be provided to the processing system **1508** of the base station **1504**. The data may be provided to the processing system **1508** by, for example, a core network. In the uplink, data to be sent to the base station **1504** from the wireless device **1502** may be provided to the processing system **1518** of the wireless device **1502**. The processing system **1508** and the processing system **1518** may implement layer 3 and layer 2 OSI functionality to process the data for transmission. Layer 2 may include an SDAP layer, a PDCP layer, an RLC layer, and a MAC layer, for example, with respect to FIG. **2**A, FIG. **2**B, FIG. **3**, and FIG. **4**A. Layer 3 may include an RRC layer as with respect to FIG. **2**B.

After being processed by processing system **1508**, the data to be sent to the wireless device **1502** may be provided to a transmission processing system **1510** of base station **1504**. Similarly, after being processed by the processing system **1518**, the data to be sent to base station **1504** may be provided to a transmission processing system **1520** of the wireless device **1502**. The transmission processing system **1510** and the transmission processing system **1520** may implement layer 1 OSI functionality. Layer 1 may include a PHY layer with respect to FIG. **2**A, FIG. **2**B, FIG. **3**, and FIG. **4**A. For transmit processing, the PHY layer may perform, for example, forward error correction coding of transport channels, interleaving, rate matching, mapping of transport channels to physical channels, modulation of physical channel, multiple-input multiple-output (MIMO) or multi-antenna processing, and/or the like.

At the base station **1504**, a reception processing system **1512** may receive the uplink transmission from the wireless device **1502**. At the wireless device **1502**, a reception processing system **1522** may receive the downlink transmission from base station **1504**. The reception processing system **1512** and the reception processing system **1522** may implement layer 1 OSI functionality. Layer 1 may include a PHY layer with respect to FIG. **2**A, FIG. **2**B, FIG. **3**, and FIG. **4**A. For receive processing, the PHY layer may perform, for example, error detection, forward error correction decoding, deinterleaving, demapping of transport channels to physical channels, demodulation of physical channels, MIMO or multi-antenna processing, and/or the like.

As shown in FIG. **15**, a wireless device **1502** and the base station **1504** may include multiple antennas. The multiple antennas may be used to perform one or more MIMO or multi-antenna techniques, such as spatial multiplexing (e.g., single-user MIMO or multi-user MIMO), transmit/receive diversity, and/or beamforming. In other examples, the wireless device **1502** and/or the base station **1504** may have a single antenna.

The processing system **1508** and the processing system **1518** maybe associated with a memory **1514** and a memory **1524**, respectively. Memory **1514** and memory **1524** (e.g., one or more non-transitory computer readable mediums) may store computer program instructions or code that may be executed by the processing system **1508** and/or the processing system **1518** to carry out one or more of the functionalities discussed in the present application. Although not shown in FIG. **15**, the transmission processing system **1510**, the transmission processing system **1520**, the reception processing system **1512**, and/or the reception processing system **1522** may be coupled to a memory (e.g., one or more non-transitory computer readable mediums) storing computer program instructions or code that may be executed to carry out one or more of their respective functionalities.

The processing system **1508** and/or the processing system **1518** may comprise one or more controllers and/or one or more processors. The one or more controllers and/or one or more processors may comprise, for example, a general-purpose processor, a digital signal processor (DSP), a microcontroller, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) and/or other programmable logic device, discrete gate and/or transistor logic, discrete hardware components, an on-board unit, or any combination thereof. The processing system **1508** and/or the processing system **1518** may perform at least one of signal coding/processing, data processing, power control, input/output processing, and/or any other functionality that may enable the wireless device **1502** and the base station **1504** to operate in a wireless environment.

The processing system **1508** and/or the processing system **1518** may be connected to one or more peripherals **1516** and one or more peripherals **1526**, respectively. The one or more peripherals **1516** and the one or more peripherals **1526** may include software and/or hardware that provide features and/or functionalities, for example, a speaker, a microphone, a keypad, a display, a touchpad, a power source, a satellite transceiver, a universal serial bus (USB) port, a hands-free headset, a frequency modulated (FM) radio unit, a media player, an Internet browser, an electronic control unit (e.g., for a motor vehicle), and/or one or more sensors (e.g., an accelerometer, a gyroscope, a temperature sensor, a radar sensor, a lidar sensor, an ultrasonic sensor, a light sensor, a camera, and/or the like). The processing system **1508** and/or the processing system **1518** may receive user input data from and/or provide user output data to the one or more peripherals **1516** and/or the one or more peripherals **1526**. The processing system **1518** in the wireless device **1502** may receive power from a power source and/or may be configured to distribute the power to the other components in the wireless device **1502**. The power source may comprise one or more sources of power, for example, a battery, a solar cell, a fuel cell, or any combination thereof. The processing system **1508** and/or the processing system **1518** may be connected to a GPS chipset **1517** and a GPS chipset **1527**, respectively. The GPS chipset **1517** and the GPS chipset

1527 may be configured to provide geographic location information of the wireless device 1502 and the base station 1504, respectively.

FIG. 16A illustrates an example structure for uplink transmission. A baseband signal representing a physical uplink shared channel may perform one or more functions. The one or more functions may comprise at least one of: scrambling; modulation of scrambled bits to generate complex-valued symbols; mapping of the complex-valued modulation symbols onto one or several transmission layers; transform precoding to generate complex-valued symbols; precoding of the complex-valued symbols; mapping of precoded complex-valued symbols to resource elements; generation of complex-valued time-domain Single Carrier-Frequency Division Multiple Access (SC-FDMA) or CP-OFDM signal for an antenna port; and/or the like. In an example, when transform precoding is enabled, a SC-FDMA signal for uplink transmission may be generated. In an example, when transform precoding is not enabled, an CP-OFDM signal for uplink transmission may be generated by FIG. 16A. These functions are illustrated as examples and it is anticipated that other mechanisms may be implemented in various embodiments.

FIG. 16B illustrates an example structure for modulation and up-conversion of a baseband signal to a carrier frequency. The baseband signal may be a complex-valued SC-FDMA or CP-OFDM baseband signal for an antenna port and/or a complex-valued Physical Random Access Channel (PRACH) baseband signal. Filtering may be employed prior to transmission.

FIG. 16C illustrates an example structure for downlink transmissions. A baseband signal representing a physical downlink channel may perform one or more functions. The one or more functions may comprise: scrambling of coded bits in a codeword to be transmitted on a physical channel; modulation of scrambled bits to generate complex-valued modulation symbols; mapping of the complex-valued modulation symbols onto one or several transmission layers; precoding of the complex-valued modulation symbols on a layer for transmission on the antenna ports; mapping of complex-valued modulation symbols for an antenna port to resource elements; generation of complex-valued time-domain OFDM signal for an antenna port; and/or the like. These functions are illustrated as examples and it is anticipated that other mechanisms may be implemented in various embodiments.

FIG. 16D illustrates another example structure for modulation and up-conversion of a baseband signal to a carrier frequency. The baseband signal may be a complex-valued OFDM baseband signal for an antenna port. Filtering may be employed prior to transmission.

A wireless device may receive from a base station one or more messages (e.g. RRC messages) comprising configuration parameters of a plurality of cells (e.g. primary cell, secondary cell). The wireless device may communicate with at least one base station (e.g. two or more base stations in dual-connectivity) via the plurality of cells. The one or more messages (e.g. as a part of the configuration parameters) may comprise parameters of physical, MAC, RLC, PCDP, SDAP, RRC layers for configuring the wireless device. For example, the configuration parameters may comprise parameters for configuring physical and MAC layer channels, bearers, etc. For example, the configuration parameters may comprise parameters indicating values of timers for physical, MAC, RLC, PCDP, SDAP, RRC layers, and/or communication channels.

A timer may begin running once it is started and continue running until it is stopped or until it expires. A timer may be started if it is not running or restarted if it is running. A timer may be associated with a value (e.g. the timer may be started or restarted from a value or may be started from zero and expire once it reaches the value). The duration of a timer may not be updated until the timer is stopped or expires (e.g., due to BWP switching). A timer may be used to measure a time period/window for a process. When the specification refers to an implementation and procedure related to one or more timers, it will be understood that there are multiple ways to implement the one or more timers. For example, it will be understood that one or more of the multiple ways to implement a timer may be used to measure a time period/window for the procedure. For example, a random access response window timer may be used for measuring a window of time for receiving a random access response. In an example, instead of starting and expiry of a random access response window timer, the time difference between two time stamps may be used. When a timer is restarted, a process for measurement of time window may be restarted. Other example implementations may be provided to restart a measurement of a time window.

A gNB may transmit one or more MAC PDUs to a wireless device. In an example, a MAC PDU may be a bit string that is byte aligned (e.g., a multiple of eight bits) in length. In an example, bit strings may be represented by tables in which the most significant bit is the leftmost bit of the first line of the table, and the least significant bit is the rightmost bit on the last line of the table. More generally, the bit string may be read from left to right and then in the reading order of the lines. In an example, the bit order of a parameter field within a MAC PDU is represented with the first and most significant bit in the leftmost bit and the last and least significant bit in the rightmost bit.

In an example, a MAC SDU may be a bit string that is byte aligned (e.g., a multiple of eight bits) in length. In an example, a MAC SDU may be included in a MAC PDU from the first bit onward. A MAC CE may be a bit string that is byte aligned (e.g., a multiple of eight bits) in length. A MAC subheader may be a bit string that is byte aligned (e.g., a multiple of eight bits) in length. In an example, a MAC subheader may be placed immediately in front of a corresponding MAC SDU, MAC CE, or padding. A MAC entity may ignore a value of reserved bits in a DL MAC PDU.

In an example, a MAC PDU may comprise one or more MAC subPDUs. A MAC subPDU of the one or more MAC subPDUs may comprise: a MAC subheader only (including padding); a MAC subheader and a MAC SDU; a MAC subheader and a MAC CE; and/or a MAC subheader and padding. The MAC SDU may be of variable size. A MAC subheader may correspond to a MAC SDU, a MAC CE, or padding.

In an example, when a MAC subheader corresponds to a MAC SDU, a variable-sized MAC CE, or padding, the MAC subheader may comprise: an R field with a one bit length; an F field with a one bit length; an LCID field with a multi-bit length; and/or an L field with a multi-bit length.

FIG. 17A shows an example of a MAC subheader with an R field, an F field, an LCID field, and an L field. In the example MAC subheader of FIG. 17A, the LCD field may be six bits in length, and the L field may be eight bits in length. FIG. 17B shows example of a MAC subheader with an R field, a F field, an LCID field, and an L field. In the example MAC subheader of FIG. 17B, the LCID field may be six bits in length, and the L field may be sixteen bits in length. When a MAC subheader corresponds to a fixed sized

MAC CE or padding, the MAC subheader may comprise: an R field with a two bit length and an LCID field with a multi-bit length. FIG. **17**C shows an example of a MAC subheader with an R field and an LCID field. In the example MAC subheader of FIG. **17**C, the LCID field may be six bits in length, and the R field may be two bits in length.

FIG. **18**A shows an example of a DL MAC PDU. Multiple MAC CEs, such as MAC CE 1 and 2, may be placed together. A MAC subPDU comprising a MAC CE may be placed before any MAC subPDU comprising a MAC SDU or a MAC subPDU comprising padding. FIG. **18**B shows an example of a UL MAC PDU. Multiple MAC CEs, such as MAC CE 1 and 2, may be placed together. A MAC subPDU comprising a MAC CE may be placed after all MAC subPDUs comprising a MAC SDU. In addition, the MAC subPDU may be placed before a MAC subPDU comprising padding.

In an example, a MAC entity of a gNB may transmit one or more MAC CEs to a MAC entity of a wireless device. FIG. **19** shows an example of multiple LCDs that may be associated with the one or more MAC CEs. The one or more MAC CEs comprise at least one of: a SP ZP CSI-RS Resource Set Activation/Deactivation MAC CE, a PUCCH spatial relation Activation/Deactivation MAC CE, a SP SRS Activation/Deactivation MAC CE, a SP CSI reporting on PUCCH Activation/Deactivation MAC CE, a TCI State Indication for UE-specific PDCCH MAC CE, a TCI State Indication for UE-specific PDSCH MAC CE, an Aperiodic CSI Trigger State Subselection MAC CE, a SP CSI-RS/CSI-IM Resource Set Activation/Deactivation MAC CE, a UE contention resolution identity MAC CE, a timing advance command MAC CE, a DRX command MAC CE, a Long DRX command MAC CE, an SCell activation/deactivation MAC CE (1 Octet), an SCell activation/deactivation MAC CE (4 Octet), and/or a duplication activation/deactivation MAC CE. In an example, a MAC CE, such as a MAC CE transmitted by a MAC entity of a gNB to a MAC entity of a wireless device, may have an LCID in the MAC subheader corresponding to the MAC CE. Different MAC CE may have different LCID in the MAC subheader corresponding to the MAC CE. For example, an LCID given by 111011 in a MAC subheader may indicate that a MAC CE associated with the MAC subheader is a long DRX command MAC CE.

In an example, the MAC entity of the wireless device may transmit to the MAC entity of the gNB one or more MAC CEs. FIG. **20** shows an example of the one or more MAC CEs. The one or more MAC CEs may comprise at least one of: a short buffer status report (BSR) MAC CE, a long BSR MAC CE, a C-RNTI MAC CE, a configured grant confirmation MAC CE, a single entry PHR MAC CE, a multiple entry PHR MAC CE, a short truncated BSR, and/or a long truncated BSR. In an example, a MAC CE may have an LCID in the MAC subheader corresponding to the MAC CE. Different MAC CE may have different LCID in the MAC subheader corresponding to the MAC CE. For example, an LCD given by 111011 in a MAC subheader may indicate that a MAC CE associated with the MAC subheader is a short-truncated command MAC CE.

In carrier aggregation (CA), two or more component carriers (CCs) may be aggregated. A wireless device may simultaneously receive or transmit on one or more CCs, depending on capabilities of the wireless device, using the technique of CA. In an example, a wireless device may support CA for contiguous CCs and/or for non-contiguous CCs. CCs may be organized into cells. For example, CCs may be organized into one primary cell (PCell) and one or more secondary cells (SCells). When configured with CA, a wireless device may have one RRC connection with a network. During an RRC connection establishment/re-establishment/handover, a cell providing NAS mobility information may be a serving cell. During an RRC connection re-establishment/handover procedure, a cell providing a security input may be a serving cell. In an example, the serving cell may denote a PCell. In an example, a gNB may transmit, to a wireless device, one or more messages comprising configuration parameters of a plurality of one or more SCells, depending on capabilities of the wireless device.

When configured with CA, a base station and/or a wireless device may employ an activation/deactivation mechanism of an SCell to improve battery or power consumption of the wireless device. When a wireless device is configured with one or more SCells, a gNB may activate or deactivate at least one of the one or more SCells. Upon configuration of an SCell, the SCell may be deactivated unless an SCell state associated with the SCell is set to "activated" or "dormant".

A wireless device may activate/deactivate an SCell in response to receiving an SCell Activation/Deactivation MAC CE. In an example, a gNB may transmit, to a wireless device, one or more messages comprising an SCell timer (e.g., sCellDeactivationTimer). In an example, a wireless device may deactivate an SCell in response to an expiry of the SCell timer.

When a wireless device receives an SCell Activation/Deactivation MAC CE activating an SCell, the wireless device may activate the SCell. In response to the activating the SCell, the wireless device may perform operations comprising SRS transmissions on the SCell; CQI/PMI/RI/CRI reporting for the SCell; PDCCH monitoring on the SCell; PDCCH monitoring for the SCell; and/or PUCCH transmissions on the SCell. In response to the activating the SCell, the wireless device may start or restart a first SCell timer (e.g., sCellDeactivationTimer) associated with the SCell. The wireless device may start or restart the first SCell timer in the slot when the SCell Activation/Deactivation MAC CE activating the SCell has been received. In an example, in response to the activating the SCell, the wireless device may (re-)initialize one or more suspended configured uplink grants of a configured grant Type 1 associated with the SCell according to a stored configuration. In an example, in response to the activating the SCell, the wireless device may trigger PHR.

When a wireless device receives an SCell Activation/Deactivation MAC CE deactivating an activated SCell, the wireless device may deactivate the activated SCell. In an example, when a first SCell timer (e.g., sCellDeactivationTimer) associated with an activated SCell expires, the wireless device may deactivate the activated SCell. In response to the deactivating the activated SCell, the wireless device may stop the first SCell timer associated with the activated SCell. In an example, in response to the deactivating the activated SCell, the wireless device may clear one or more configured downlink assignments and/or one or more configured uplink grants of a configured uplink grant Type 2 associated with the activated SCell. In an example, in response to the deactivating the activated SCell, the wireless device may: suspend one or more configured uplink grants of a configured uplink grant Type 1 associated with the activated SCell; and/or flush HARQ buffers associated with the activated SCell.

When an SCell is deactivated, a wireless device may not perform operations comprising: transmitting SRS on the

SCell; reporting CQI/PMI/RI/CRI for the SCell; transmitting on UL-SCH on the SCell; transmitting on RACH on the SCell; monitoring at least one first PDCCH on the SCell; monitoring at least one second PDCCH for the SCell; and/or transmitting a PUCCH on the SCell. When at least one first PDCCH on an activated SCell indicates an uplink grant or a downlink assignment, a wireless device may restart a first SCell timer (e.g., sCellDeactivationTimer) associated with the activated SCell. In an example, when at least one second PDCCH on a serving cell (e.g. a PCell or an SCell configured with PUCCH, i.e. PUCCH SCell) scheduling the activated SCell indicates an uplink grant or a downlink assignment for the activated SCell, a wireless device may restart the first SCell timer (e.g., sCellDeactivationTimer) associated with the activated SCell. In an example, when an SCell is deactivated, if there is an ongoing random access procedure on the SCell, a wireless device may abort the ongoing random access procedure on the SCell.

FIG. **21**A shows an example of an SCell Activation/Deactivation MAC CE of one octet. A first MAC PDU subheader with a first LCD (e.g., '111010' as shown in FIG. **19**) may identify the SCell Activation/Deactivation MAC CE of one octet. The SCell Activation/Deactivation MAC CE of one octet may have a fixed size. The SCell Activation/Deactivation MAC CE of one octet may comprise a single octet. The single octet may comprise a first number of C-fields (e.g. seven) and a second number of R-fields (e.g., one). FIG. **21**B shows an example of an SCell Activation/Deactivation MAC CE of four octets. A second MAC PDU subheader with a second LCD (e.g., '111001' as shown in FIG. **19**) may identify the SCell Activation/Deactivation MAC CE of four octets. The SCell Activation/Deactivation MAC CE of four octets may have a fixed size. The SCell Activation/Deactivation MAC CE of four octets may comprise four octets. The four octets may comprise a third number of C-fields (e.g., 31) and a fourth number of R-fields (e.g., **1**).

In FIG. **21**A and/or FIG. **21**B, a C_i field may indicate an activation/deactivation status of an SCell with an SCell index i if an SCell with SCell index i is configured. In an example, when the C_i field is set to one, an SCell with an SCell index i may be activated. In an example, when the C_i field is set to zero, an SCell with an SCell index i may be deactivated. In an example, if there is no SCell configured with SCell index i, the wireless device may ignore the C_i field. In FIG. **21**A and FIG. **21**B, an R field may indicate a reserved bit. The R field may be set to zero.

A base station (gNB) may configure a wireless device (UE) with uplink (UL) bandwidth parts (BWPs) and downlink (DL) BWPs to enable bandwidth adaptation (BA) on a PCell. If carrier aggregation is configured, the gNB may further configure the UE with at least DL BWP(s) (i.e., there may be no UL BWPs in the UL) to enable BA on an SCell. For the PCell, an initial active BWP may be a first BWP used for initial access. For the SCell, a first active BWP may be a second BWP configured for the UE to operate on the SCell upon the SCell being activated. In paired spectrum (e.g. FDD), a gNB and/or a UE may independently switch a DL BWP and an UL BWP. In unpaired spectrum (e.g. TDD), a gNB and/or a UE may simultaneously switch a DL BWP and an UL BWP.

In an example, a gNB and/or a UE may switch a BWP between configured BWPs by means of a DCI or a BWP inactivity timer. When the BWP inactivity timer is configured for a serving cell, the gNB and/or the UE may switch an active BWP to a default BWP in response to an expiry of the BWP inactivity timer associated with the serving cell. The default BWP may be configured by the network. In an example, for FDD systems, when configured with BA, one UL BWP for each uplink carrier and one DL BWP may be active at a time in an active serving cell. In an example, for TDD systems, one DL/UL BWP pair may be active at a time in an active serving cell. Operating on the one UL BWP and the one DL BWP (or the one DL/UL pair) may improve UE battery consumption. BWPs other than the one active UL BWP and the one active DL BWP that the UE may work on may be deactivated. On deactivated BWPs, the UE may: not monitor PDCCH; and/or not transmit on PUCCH, PRACH, and UL-SCH.

In an example, a serving cell may be configured with at most a first number (e.g., four) of BWPs. In an example, for an activated serving cell, there may be one active BWP at any point in time. In an example, a BWP switching for a serving cell may be used to activate an inactive BWP and deactivate an active BWP at a time. In an example, the BWP switching may be controlled by a PDCCH indicating a downlink assignment or an uplink grant. In an example, the BWP switching may be controlled by a BWP inactivity timer (e.g., bwp-InactivityTimer). In an example, the BWP switching may be controlled by a MAC entity in response to initiating a Random Access procedure. Upon addition of an SpCell or activation of an SCell, one BWP may be initially active without receiving a PDCCH indicating a downlink assignment or an uplink grant. The active BWP for a serving cell may be indicated by RRC and/or PDCCH. In an example, for unpaired spectrum, a DL BWP may be paired with a UL BWP, and BWP switching may be common for both UL and DL.

FIG. **22** shows an example of BWP switching on an SCell. In an example, a UE may receive RRC message comprising parameters of a SCell and one or more BWP configuration associated with the SCell. The RRC message may comprise: RRC connection reconfiguration message (e.g., RRCReconfiguration); RRC connection reestablishment message (e.g., RRCRestablishment); and/or RRC connection setup message (e.g., RRCSetup). Among the one or more BWPs, at least one BWP may be configured as the first active BWP (e.g., BWP 1), one BWP as the default BWP (e.g., BWP 0). The UE may receive a MAC CE to activate the SCell at n^{th} slot. The UE may start a SCell deactivation timer (e.g., sCellDeactivationTimer), and start CSI related actions for the SCell, and/or start CSI related actions for the first active BWP of the SCell. The UE may start monitoring a PDCCH on BWP 1 in response to activating the SCell.

In an example, the UE may start restart a BWP inactivity timer (e.g., bwp-InactivityTimer) at m-th slot in response to receiving a DCI indicating DL assignment on BWP 1. The UE may switch back to the default BWP (e.g., BWP 0) as an active BWP when the BWP inactivity timer expires, at s-th slot. The UE may deactivate the SCell and/or stop the BWP inactivity timer when the sCellDeactivationTimer expires.

In an example, a MAC entity may apply normal operations on an active BWP for an activated serving cell configured with a BWP comprising: transmitting on UL-SCH; transmitting on RACH; monitoring a PDCCH; transmitting PUCCH; receiving DL-SCH; and/or (re-) initializing any suspended configured uplink grants of configured grant Type 1 according to a stored configuration, if any.

In an example, on an inactive BWP for each activated serving cell configured with a BWP, a MAC entity may: not transmit on UL-SCH; not transmit on RACH; not monitor a PDCCH; not transmit PUCCH; not transmit SRS, not receive DL-SCH; clear any configured downlink assignment and configured uplink grant of configured grant Type 2; and/or suspend any configured uplink grant of configured Type 1.

In an example, if a MAC entity receives a PDCCH for a BWP switching of a serving cell while a Random Access procedure associated with this serving cell is not ongoing, a UE may perform the BWP switching to a BWP indicated by the PDCCH. In an example, if a bandwidth part indicator field is configured in DCI format 1_1, the bandwidth part indicator field value may indicate the active DL BWP, from the configured DL BWP set, for DL receptions. In an example, if a bandwidth part indicator field is configured in DCI format 0_1, the bandwidth part indicator field value may indicate the active UL BWP, from the configured UL BWP set, for UL transmissions.

In an example, for a primary cell, a UE may be provided by a higher layer parameter Default-DL-BWP a default DL BWP among the configured DL BWPs. If a UE is not provided a default DL BWP by the higher layer parameter Default-DL-BWP, the default DL BWP is the initial active DL Bipin an example, a UE may be provided by higher layer parameter bwp-InactivityTimer, a timer value for the primary cell. If configured, the UE may increment the timer, if running, every interval of 1 millisecond for frequency range 1 or every 0.5 milliseconds for frequency range 2 if the UE may not detect a DCI format 1_1 for paired spectrum operation or if the UE may not detect a DCI format 1_1 or DCI format 0_1 for unpaired spectrum operation during the interval.

In an example, if a UE is configured for a secondary cell with higher layer parameter Default-DL-BWP indicating a default DL BWP among the configured DL BWPs and the UE is configured with higher layer parameter bwp-InactivityTimer indicating a timer value, the UE procedures on the secondary cell may be same as on the primary cell using the timer value for the secondary cell and the default DL BWP for the secondary cell.

In an example, if a UE is configured by higher layer parameter Active-BWP-DL-SCell a first active DL BWP and by higher layer parameter Active-BWP-UL-SCell a first active UL BWP on a secondary cell or carrier, the UE may use the indicated DL BWP and the indicated UL BWP on the secondary cell as the respective first active DL BWP and first active UL BWP on the secondary cell or carrier.

In an example, a set of PDCCH candidates for a wireless device to monitor is defined in terms of PDCCH search space sets. A search space set comprises a CSS set or a USS set. A wireless device monitors PDCCH candidates in one or more of the following search spaces sets: a Type0-PDCCH CSS set configured by pdcch-ConfigSIB1 in MIB or by searchSpaceSIB1 in PDCCH-ConfigCommon or by searchSpaceZero in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a SI-RNTI on the primary cell of the MCG, a Type0A-PDCCH CSS set configured by searchSpaceOtherSystemInformation in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a SI-RNTI on the primary cell of the MCG, a Type1-PDCCH CSS set configured by ra-SearchSpace in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a RA-RNTI or a TC-RNTI on the primary cell, a Type2-PDCCH CSS set configured by pagingSearchSpace in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a P-RNTI on the primary cell of the MCG, a Type3-PDCCH CSS set configured by SearchSpace in PDCCH-Config with searchSpace Type=common for DCI formats with CRC scrambled by INT-RNTI, SFI-RNTI, TPC-PUSCH-RNTI, TPC-PUCCH-RNTI, or TPC-SRS-RNTI and, only for the primary cell, C-RNTI, MCS-C-RNTI, or CS-RNTI(s), and a USS set configured by SearchSpace in PDCCH-Config with searchSpaceType=ue-Specific for DCI formats with CRC scrambled by C-RNTI, MCS-C-RNTI, SP-CSI-RNTI, or CS-RNTI(s).

In an example, a wireless device determines a PDCCH monitoring occasion on an active DL BWP based on one or more PDCCH configuration parameters comprising: a PDCCH monitoring periodicity, a PDCCH monitoring offset, and a PDCCH monitoring pattern within a slot. For a search space set (SS s), the wireless device determines that a PDCCH monitoring occasion(s) exists in a slot with number $n_{s,f}^{\mu}$ in a frame with number n_f if $(n_f \cdot N_{slot}^{frame,\mu} + n_{s,f}^{\mu} - o_s) \bmod k_s = 0$. $N_{slot}^{frame,\mu}$ is a number of slot in a frame when numerology p is configured. o_s is a slot offset indicated in the PDCCH configuration parameters. k_s is a PDCCH monitoring periodicity indicated in the PDCCH configuration parameters. The wireless device monitors PDCCH candidates for the search space set for T_s consecutive slots, starting from slot $n_{s,f}^{\mu}$, and does not monitor PDCCH candidates for search space set s for the next $k_s - T_s$ consecutive slots. In an example, a USS at CCE aggregation level $L \in \{1, 2, 4, 8, 16\}$ is defined by a set of PDCCH candidates for CCE aggregation level L. If a wireless device is configured with CrossCarrierSchedulingConfig for a serving cell, the carrier indicator field value corresponds to the value indicated by CrossCarrierSchedulingConfig.

In an example, a wireless device decides, for a search space set s associated with CORESET p, CCE indexes for aggregation level L corresponding to PDCCH candidate $m_{s,n_{CI}}$ of the search space set in slot $n_{s,f}^{\mu}$ for an active DL BWP of a serving cell corresponding to carrier indicator field value n_{CI} as

$$L \cdot \left\{ \left(Y_{p,n_{s,f}^{\mu}} + \left\lfloor \frac{m_{s,n_{CI}} \cdot N_{CCE,p}}{L \cdot M_{s,max}^{(L)}} \right\rfloor + n_{CI} \right) \bmod \lfloor N_{CCE,p} / L \rfloor \right\} + i,$$

where, $Y_{p,n_{s,f}^{\mu}} = 0$ for any CSS; $Y_{p,n_{s,f}^{\mu}} = (A_p \cdot Y_{p,n_{s,f}^{\mu}-1}) \bmod D$ for a USS, $Y_{p,-1} = n_{RNTI} \neq 0$, $A_p = 39827$ for p mod 3=0, $A_p = 39829$ for p mod 3=1, $A_p = 39839$ for p mod 3=2, and D=65537; i=0, . . . , L−1; $N_{CCE,p}$ is the number of CCEs, numbered from 0 to $N_{CCE,p} - 1$, in CORESET p; n_{CI} is the carrier indicator field value if the wireless device is configured with a carrier indicator field by CrossCarrierSchedulingConfig for the serving cell on which PDCCH is monitored; otherwise, including for any CSS, $n_{CI} = 0$; $m_{s,n_{CI}} = 0, \ldots, M_{s,n_{CI}}^{(L)} - 1$, where $M_{s,n_{CI}}^{(L)}$ is the number of PDCCH candidates the wireless device is configured to monitor for aggregation level L of a search space sets for a serving cell corresponding to n_{CI}; for any CSS, $M_{s,max}^{(L)} = M_{s,0}^{(L)}$; for a USS, $M_{s,max}^{(L)}$ is the maximum of $MM_{s,n_{CI}}^{(L)}$ over all configured n_{CI} values for a CCE aggregation level L of search space set s; and the RNTI value used for n_{RNTI} is the C-RNTI.

In an example, a UE may monitor a set of PDCCH candidates according to configuration parameters of a search space set comprising a plurality of search spaces (SSs). The UE may monitor a set of PDCCH candidates in one or more CORESETs for detecting one or more DCIs. Monitoring may comprise decoding one or more PDCCH candidates of the set of the PDCCH candidates according to the monitored DCI formats. Monitoring may comprise decoding a DCI content of one or more PDCCH candidates with possible (or configured) PDCCH locations, possible (or configured) PDCCH formats (e.g., number of CCEs, number of PDCCH candidates in common SSs, and/or number of PDCCH candidates in the UE-specific SSs) and possible (or configured) DCI formats. The decoding may be referred to as blind decoding.

FIG. **23** shows an example of configuration of a SS. In an example, one or more SS configuration parameters of a SS may comprise at least one of: a SS ID (searchSpaceId), a control resource set ID (controlResourceSetId), a monitoring slot periodicity and offset parameter (monitoringSlotPeriodicityAndOffset), a SS time duration value (duration), a monitoring symbol indication (monitoringSymbolsWithinSlot), a number of candidates for an aggregation level (nrofCandidates), and/or a SS type indicating a common SS type or a UE-specific SS type (searchSpaceType). The monitoring slot periodicity and offset parameter may indicate slots (e.g. in a radio frame) and slot offset (e.g., related to a starting of a radio frame) for PDCCH monitoring. The monitoring symbol indication may indicate on which symbol(s) of a slot a wireless device may monitor PDCCH on the SS. The control resource set ID may identify a control resource set on which a SS may be located.

FIG. **24** shows an example of configuration of a control resource set (CORESET). In an example, a base station may transmit to a wireless device one or more configuration parameters of a CORESET. The configuration parameters may comprise at least one of: a CORESET ID identifying the CORESET, a frequency resource indication, a time duration parameter indicating a number of symbols of the CORESET, a CCE-REG mapping type indicator, a plurality of TCI states, an indicator indicating whether a TCI is present in a DCI, and the like. The frequency resource indication, comprising a number of bits (e.g., 45 bits), indicates frequency domain resources, each bit of the indication corresponding to a group of 6 RBs, with grouping starting from the first RB group in a BWP of a cell (e.g., SpCell, SCell). The first (left-most/most significant) bit corresponds to the first RB group in the BWP, and so on. A bit that is set to 1 indicates that an RB group, corresponding to the bit, belongs to the frequency domain resource of this CORESET. Bits corresponding to a group of RBs not fully contained in the BWP within which the CORESET is configured are set to zero.

FIG. **25**A shows an example of flow chart of data reception at a wireless device. In an example, a wireless device receives one or more RRC messages comprising configuration parameters of a cell, the cell comprising one or more BWPs. The configuration parameters indicate one or more CORESETs and/or one or more search spaces (SSs) configured on a BWP of the one or more BWPs. The one or more CORESETs and/or the one or more SSs may be implemented as examples of FIG. **23** and/or FIG. **24**.

As shown in FIG. **25**A, the wireless device, based on the one or more RRC messages, may monitor PDCCH candidate(s) on a SS of the one or more SSs of a CORESET of the one or more CORESETs of an active BWP, for detecting a DCI indicating a downlink assignment over a PDSCH. Monitoring PDCCH candidate(s) on a SS may comprises attempting to decode a DCI content of the PDCCH candidates with one or more PDCCH monitoring locations, one or more CCEs based on aggregation levels, a number of PDCCH candidates, and one or more DCI formats. The one or more RRC messages may indicate the number of PDCCH candidates for each aggregation level on a SS. The wireless device may determine a number of CCEs for each aggregation level for detecting a DCI. In an example, the wireless device may determine **1** CCE for detecting DCI when aggregation level is 1, 2 CCEs when aggregation level is 2, 4 CCEs when aggregation level is 4, 8 CCEs when aggregation level is 8, and 16 CCEs when aggregation level is 16. FIG. **25**B shows an example of CCEs and REGs on a BWP.

In an example, a wireless device determines that a PDCCH monitoring occasion(s) for an SS exist in a slot with number $n_{s,f}^{\mu}$ in a frame with number n_f if $(n_f \cdot N_{slot}^{frame,\mu} + n_{s,f}^{\mu} - o_s) \bmod k_s = 0$. $N_{slot}^{frame,\mu}$ is a number of slot in a frame when numerology μ is configured. o_s is a slot offset indicated in configuration parameters of the SS. k_s is a PDCCH monitoring periodicity indicated in the configuration parameters of the SS. The wireless device monitors PDCCH candidates for the SS for T_s consecutive slots, starting from slot $n_{s,f}^{\mu}$. The wireless device may not monitor PDCCH candidates for the SS for the next $k_s - T_s$ consecutive slots. In an example, a USS at CCE aggregation level $L \in \{1, 2, 4, 8, 16\}$ is defined by a set of PDCCH candidates for CCE aggregation level L.

As shown in FIG. **25**A, when monitoring PDCCH candidate(s) on a SS, the wireless device may receive (or decode successfully) a DCI, on one or more CCEs. The one or more CCEs may start from a starting CCE index. The DCI may comprise a time resource indicator for a downlink assignment, a frequency resource indicator for the downlink assignment, a PUCCH resource indicator (PM), a PDSCH-to-HARQ_feedback timing indicator.

In response to receiving the DCI, the wireless device may receive symbols of a transport block (TB) via the downlink assignment. The wireless device may attempt to decode the TB based on the received symbols. The wireless device may generate a positive acknowledgement (ACK) in response to the decoding being successful. The wireless device may generate a negative acknowledgement (NACK) in response to the decoding not being successful.

In an example, the wireless device may transmit the ACK/NACK via a PUCCH resource at a time determined based on a value of the PDSCH-to-HARQ_feedback timing indicator. The wireless device may determine the PUCCH resource based on the PM of the DCI, the starting CCE index of the one or more CCEs on which the wireless device receives the DCI, a cell index of a cell for which the wireless device monitors the PDCCH candidates, a RNTI value for receiving the DCI.

FIG. **25**B shows an example of PUCCH resource determination. In an example, a wireless device may receive one or more RRC messages comprising configuration parameters of a BWP of a cell, the BWP, with a bandwidth, comprising one or more radio resource unites (e.g., RBs as shown in FIG. **8**). The configuration parameters may indicate resource allocation of one or more CORESETs. A CORESET may consist of $N_{RB}^{CORESET}$ (e.g., indicated by a RRC message as shown in FIG. **24**) resource blocks in the frequency domain and $N_{symb}^{CORESET} \in \{1, 2, 3\}$ (e.g., indicated by an RRC message as shown in FIG. **24**) symbols in the time domain. The wireless device may determine $N_{RB}^{CORESET}$ based on high layer parameter (e.g., frequencyDomainResources) of the CORESET. As shown in FIG. **25**B, the parameter frequencyDomainResources may comprise a bitmap of frequency location indication, the bitmap comprising one or more bits (e.g., 45 bits). Each bit of the bitmap corresponds a group of 6 RBs (e.g., an RBG as shown in FIG. **25**B), with grouping starting from the first RB group in the BWP. The first (left-most/most significant) bit of the bitmap corresponds to the first RB group in the BWP, and so on. A bit that is set to 1 indicates that an RB group, corresponding to the bit, belongs to the frequency domain resource of the CORESET. A bit that is set to 0 indicates that an RB group, corresponding to the bit, does not belong to the frequency domain resource of the CORESET.

In an example, the wireless device may monitor a PDCCH candidate of a SS, on one or more CCEs with the RBGs of the CORESET on an active BWP. A CCE may consist of a number (e.g., 6) of resource-element groups (REGs). A REG may comprise one RB during one OFDM symbol. REGs within a CORESET are numbered in increasing order in a time-first manner, starting with 0 for the first OFDM symbol and the lowest-numbered resource block in the CORESET. In an example, a CORESET is configured with one CCE-to-REG mapping indicator.

In an example, CCE-to-REG mapping for a CORESET may be interleaved or non-interleaved and is described by REG bundles:

- REG bundle i is defined as REGs {iL, iL+1, . . . , iL+L−1} where L is the REG bundle size, i=0, 1, . . . , $N_{REG}^{CORESET}$/L−1, and $N_{REG}^{CORESET}=N_{RB}^{CORESET}N_{symb}^{CORESET}N_{symb}^{CORESET}$ is the number of REGs in the CORESET;
- CCE j consists of REG bundles {f (6j/L), f (6j/L+1), . . . , f (6j/L+6/L−1)} where f(•) is an interleaver.

In an example, for non-interleaved CCE-to-REG mapping, L=6 and f (x)=x. In an example, for interleaved CCE-to-REG mapping, L∈{2,6} for $N_{symb}^{CORESET}=1$ and L ∈{$N_{symb}^{CORESET}$, 6} for $N_{symb}^{CORESET}\in\{2,3\}$. The interleaver is defined by:

$$f(x)=(rC+c+n_{shift})\bmod(N_{REG}^{CORESET}/L)x=cR+rr=0,1,\ldots,R-1c=0,1,\ldots,C-1C=N_{REG}^{CORESET}/(LR)$$

$$f(x)=(rC+c+n_{shift})\bmod(N_{REG}^{CORESET}/L)x=cR+rr=0,1,\ldots,R-1c=0,1,\ldots,C-1C=N_{REG}^{CORESET}/(LR)$$

$$f(x)=(rC+c+n_{shift})\bmod(N_{REG}^{CORESET}/L)x=cR+rr=0,1,\ldots,R-1c=0,1,\ldots,C-1C=N_{REG}^{CORESET}/(LR)$$

$$f(x)=(rC+c+n_{shift})\bmod(N_{REG}^{CORESET}/L)x=cR+rr=0,1,\ldots,R-1c=0,1,\ldots,C-1C=N_{REG}^{CORESET}/(LR)$$

$$f(x)=(rC+c+n_{shift})\bmod(N_{REG}^{CORESET}/L)x=cR+rr=0,1,\ldots,R-1c=0,1,\ldots,C-1C=N_{REG}^{CORESET}/(LR)$$

where R∈{2, 3, 6}.

In an example, a set of PDCCH candidates for a UE to monitor is defined in terms of PDCCH search space sets. A search space set may be a CSS set or a USS set. A UE monitors PDCCH candidates in one or more of the following search spaces sets:

- a Type0-PDCCH CSS set configured by pdcch-ConfigSIB1 in MIB or by searchSpaceSIB1 in PDCCH-ConfigCommon or by searchSpaceZero in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a SI-RNTI on the primary cell of the MCG;
- a Type0A-PDCCH CSS set configured by searchSpaceOtherSystemInformation in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a SI-RNTI on the primary cell of the MCG;
- a Type1-PDCCH CSS set configured by ra-SearchSpace in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a RA-RNTI or a TC-RNTI on the primary cell;
- a Type2-PDCCH CSS set configured by pagingSearchSpace in PDCCH-ConfigCommon for a DCI format with CRC scrambled by a P-RNTI on the primary cell of the MCG;
- a Type3-PDCCH CSS set configured by SearchSpace in PDCCH-Config with searchSpaceType=common for DCI formats with CRC scrambled by INT-RNTI, SFI-RNTI, TPC-PUSCH-RNTI, TPC-PUCCH-RNTI, or TPC-SRS-RNTI and, only for the primary cell, C-RNTI, MCS-C-RNTI, or CS-RNTI(s), and
- a USS set configured by SearchSpace in PDCCH-Config with searchSpaceType=ue-Specific for DCI formats with CRC scrambled by C-RNTI, MCS-C-RNTI, SP-CSI-RNTI, or CS-RNTI(s).

In an example, a wireless device decides, for a search space set s associated with CORESET p, CCE indexes for aggregation level L corresponding to PDCCH candidate $m_{s,n_{CI}}$ of the search space set in slot $n_{s,f}^{\mu}$ for an active DL BWP of a serving cell corresponding to carrier indicator field value n_{CI} as

$$L\cdot\left\{\left(Y_{p,n_{s,f}^{\mu}}+\left\lfloor\frac{m_{s,n_{CI}}\cdot N_{CCE,p}}{L\cdot M_{s,max}^{(L)}}\right\rfloor+n_{CI}\right)\bmod\lfloor N_{CCE,p}/L\rfloor\right\}+i,$$

where, $Y_{p,n_{s,f}^{\mu}}=0$ for any CSS; $Y_{p,n_{s,f}^{\mu}}=(A_p\cdot Y_{p,n_{s,f}^{\mu}-1})\bmod D$ for a USS, $Y_{p,-1}=n_{RNTI}\neq0$, $A_p=39827$ for p mod 3=0, $A_p=39829$ for p mod 3=1, $A_p=39839$ for p mod 3=2, and D=65537; i=0, . . . , L−1; $N_{CCE,p}$ is the number of CCEs, numbered from 0 to $N_{CCE,p}-1$, in CORESET p; n_{CI} is the carrier indicator field value if the wireless device is configured with a carrier indicator field by CrossCarrierSchedulingConfig for the serving cell on which PDCCH is monitored; otherwise, including for any CSS, $n_{CI}=0$; $m_{s,n_{CI}}=0,\ldots,M_{s,n_{CI}}^{(L)}-1$, where $M_{s,n_{CI}}^{(L)}$ is the number of PDCCH candidates the wireless device is configured to monitor for aggregation level L of a search space sets for a serving cell corresponding to n_{CI}; for any CSS, $M_{s,max}^{(L)}=M_{s,0}^{(L)}$; for a USS, $M_{s,max}^{(L)}$ is the maximum of $M_{s,n_{CI}}^{(L)}$ over all configured n_{CI} values for a CCE aggregation level L of search space set s; and the RNTI value used for n_{RNTI} is the C-RNTI.

As shown in FIG. **25**B, a BWP of a cell may comprise M RBGs, indexing from RBG 0 to RBG M−1. A CORESET configured on the BWP may occupy a number of RBGs of the M RBGs, based on a bitmap (e.g., frequencyDomainResources). Bit **0**, corresponding to RBG 0, being set to 1, may indicate RBG 0 belong to the CORESET, and so on. Radio resources of the number of RBGs may map to a number of CCEs, the number of CCEs indexed from CCE 0 to CCE N−1, based on CCE-to-REG mapping indicator (e.g., cce-REG-MappingType). The wireless device may monitor PDCCH candidates of a SS on a subset of the number of CCEs, e.g., comprising CCE 2, CCE 4, CCE 6, and so on.

In an example, the wireless device may receive a DCI on the SS, starting from CCE 2, based on the equation above. The wireless device may determine, for HARQ-ACK feedback, a PUCCH resource based on a PRI value of the DCI, a starting CCE index (e.g., CCE 2 in the example of FIG. **25**B).

In an example, a wireless device may not have dedicated PUCCH resource configuration. The wireless device may determine a PUCCH resource set based on a predefined PUCCH resource table, for transmission of HARQ-ACK information on PUCCH. The PUCCH resource set includes sixteen resources, each corresponding to a PUCCH format, a starting symbol, a duration, a PRB offset, and a cyclic shift index set for a PUCCH transmission.

In an example, the wireless device may determine a PUCCH resource with index r_{PUCCH}, $0 \le r_{PUCCH} \le 15$, as

$$r_{PUCCH} = \left\lfloor \frac{2 \cdot n_{CCE,0}}{N_{CCE}} \right\rfloor + 2 \cdot \Delta_{PRI},$$

where N_{CCE} is a number of CCEs (e.g., K in the example of FIG. **25**B) in a CORESET of a PDCCH reception with the DCI, $n_{CCE,0}$ is the index of a first CCE (e.g., 2 in the example of FIG. **25**B) for the PDCCH reception, and Δ_{PRI} is a value of the PRI field in the DCI. In the example of FIG. **25**B, $r_{PUCCH}=2$.

In an example, a wireless device may be configured with dedicated PUCCH resource configuration by higher layers. In an example, a PUCCH resource may comprise: a PUCCH resource index (e.g., provided by pucch-ResourceId), an index of the first PRB prior to frequency hopping or for no frequency hopping by startingPRB, an index of the first PRB after frequency hopping by secondHopPRB, an indication for intra-slot frequency hopping by intraSlotFrequencyHopping, and/or a configuration for a PUCCH format, from PUCCH format 0 through PUCCH format 4, provided by format.

In an example, when a wireless device transmits HARQ-ACK information in a PUCCH in response to detecting a last DCI (e.g., DCI format 1_0 or DCI format 1_1) in a PDCCH reception, among multiple DCIs with a value of the PDSCH-to-HARQ_feedback timing indicator field indicating a same slot for the PUCCH transmission, the wireless device determines a PUCCH resource, from a set of PUCCH resources (e.g., the first set when configured with multiple sets of PUCCH resources), with index r_{pucchH}, $0 \le r_{PUCCH} \le R_{PUCCH}-1$, as

$$r_{PUCCH} = \begin{cases} \left\lfloor \frac{n_{CCE,p} \cdot \lceil R_{PUCCH}/8 \rceil}{N_{CCE,p}} \right\rfloor + \Delta_{PRI} \cdot \left\lceil \frac{R_{PUCCH}}{8} \right\rceil & \text{if } \Delta_{PRI} < R_{PUCCH} \bmod 8 \\ \left\lfloor \frac{n_{CCE,p} \cdot \lceil R_{PUCCH}/8}{N_{CCE,p}} \right\rfloor + \Delta_{PRI} \cdot \left\lfloor \frac{R_{PUCCH}}{8} \right\rfloor + R_{PUCCH} \bmod 8 & \text{if } \Delta_{PRI} \ge R_{PUCCH} \bmod 8 \end{cases}$$

when the size R_{PUCCH} of resourceList of the first set of PUCCH resources is larger than eight. In an example, $N_{CCE,p}$ is a number of CCEs (e.g., K in the example of FIG. **25**B) in CORESET p of the PDCCH reception for the DCI. $n_{CCE,p}$ is the index of a first CCE (e.g., 2 in the example of FIG. **25**B) for the PDCCH reception, and Δ_{PRI} is a value of the PM field in the DCI.

In an example, a wireless device may transmit one or more uplink control information (UCI) via one or more PUCCH resources to a base station. The one or more UCI may comprise at least one of: HARQ-ACK information; scheduling request (SR); and/or CSI report. In an example, a PUCCH resource may be identified by at least: frequency location (e.g., starting PRB); and/or a PUCCH format. The PUCCH format may be configured with an initial cyclic shift value of a base sequence and a time domain location parameter (e.g., starting symbol index). In an example, a PUCCH format may comprise at least one of PUCCH format 0, PUCCH format 1, PUCCH format 2, PUCCH format 3, or PUCCH format 4. A PUCCH format 0 may have a length of 1 or 2 OFDM symbols and be less than or equal to 2 bits. A PUCCH format 1 may occupy a number between 4 and 14 of OFDM symbols and be less than or equal to 2 bits. A PUCCH format 2 may occupy 1 or 2 OFDM symbols and be greater than 2 bits. A PUCCH format 3 may occupy a number between 4 and 14 of OFDM symbols and be greater than 2 bits. A PUCCH format 4 may occupy a number between 4 and 14 of OFDM symbols and be greater than 2 bits. The PUCCH resource may be configured on a PCell, or a PUCCH secondary cell.

In an example, when configured with multiple UL BWPs, a base station may transmit to a wireless device, one or more RRC messages comprising configuration parameters of one or more PUCCH resource sets (e.g., 1, 2, 3, 4, or greater than 4) on an UL BWP of the multiple UL BWPs. Each PUCCH resource set may be configured with a PUCCH resource set index, a list of PUCCH resources with each PUCCH resource being identified by a PUCCH resource identifier (e.g., pucch-Resourceid), and/or a maximum number of UCI information bits a wireless device may transmit using one of the list of PUCCH resources in the PUCCH resource set.

In an example, when configured with one or more PUCCH resource sets, a wireless device may select one of the one or more PUCCH resource sets based on a bit length of UCI information bits (e.g., HARQ-ARQ bits, SR, and/or CSI) the wireless device will transmit. In an example, when the bit length of UCI information bits is less than or equal to 2, the wireless device may select a first PUCCH resource set with the PUCCH resource set index equal to "0". In an example, when the bit length of UCI information bits is greater than 2 and less than or equal to a first configured value, the wireless device may select a second PUCCH resource set with the PUCCH resource set index equal to "1". In an example, when the bit length of UCI information bits is greater than the first configured value and less than or equal to a second configured value, the wireless device may select a third PUCCH resource set with the PUCCH resource set index equal to "2". In an example, when the bit length of UCI information bits is greater than the second configured value and less than or equal to a third value (e.g., 1706), the wireless device may select a fourth PUCCH resource set with the PUCCH resource set index equal to "3".

In an example, a wireless device may determine, based on a number of uplink symbols of UCI transmission and a number of UCI bits, a PUCCH format from a plurality of PUCCH formats comprising PUCCH format 0, PUCCH format 1, PUCCH format 2, PUCCH format 3 and/or PUCCH format 4. In an example, the wireless device may transmit UCI in a PUCCH using PUCCH format 0 if the transmission is over 1 symbol or 2 symbols and the number of HARQ-ACK information bits with positive or negative SR (HARQ-ACK/SR bits) is 1 or 2. The PUCCH format 0 may be based on DFT-spread OFDM, e.g., to reduce cubic metric. In an example, the wireless device may transmit UCI in a PUCCH using PUCCH format 1 if the transmission is over 4 or more symbols and the number of HARQ-ACK/SR bits is 1 or 2. The PUCCH format 1 may be based on DFT-spread OFDM, e.g., to reduce cubic metric. In an example, the wireless device may transmit UCI in a PUCCH using PUCCH format 2 if the transmission is over 1 symbol or 2 symbols and the number of UCI bits is more than 2. The PUCCH format 2 may be based on OFDM. In an example, the wireless device may transmit UCI in a PUCCH using PUCCH format 3 if the transmission is over 4 or more symbols, the number of UCI bits is more than 2 and PUCCH resource does not include an orthogonal cover code. The PUCCH format 3 may be based on DFT-spread OFDM, e.g., to reduce cubic metric. In an example, the wireless device may transmit UCI in a PUCCH using PUCCH format 4 if the transmission is over 4 or more symbols, the number of UCI bits is more than 2 and the PUCCH resource includes an orthogonal cover code. The PUCCH format 4 may be based on DFT-spread OFDM, e.g., to reduce cubic metric.

In an example, in order to transmit HARQ-ACK information on a PUCCH resource, a wireless device may determine the PUCCH resource from a PUCCH resource set. The PUCCH resource set may be determined as mentioned above. The wireless device may determine the PUCCH resource based on a PUCCH resource indicator field in a DCI (e.g., with a DCI format 1_0 or DCI for 1_1) received on a PDCCH. A 3-bit PUCCH resource indicator field in the DCI may indicate one of eight PUCCH resources in the PUCCH resource set. The wireless device may transmit the HARQ-ACK information in a PUCCH resource indicated by the 3-bit PUCCH resource indicator field in the DCI.

FIG. **26** shows an example of mapping of PUCCH resource indication (PRI) field value to PUCCH resource in a PUCCH resource set (e.g., with maximum 8 PUCCH resources). In an example, when the PUCCH resource indicator in the DCI (e.g., DCI format 1_0 or 1_1) is '000', the wireless device may determine a PUCCH resource identified by a PUCCH resource identifier (e.g., pucch-Resourdceid) with a first value in the PUCCH resource list of the PUCCH resource set. When the PUCCH resource indicator in the DCI (e.g., DCI format 1_0 or 1_1) is '001', the wireless device may determine a PUCCH resource identified by a PUCCH resource identifier (e.g., pucch-Resourdceid) with a second value in the PUCCH resource list of the PUCCH resource set, etc. Similarly, in order to transmit HARQ-ACK information, SR and/or CSI multiplexed in a PUCCH, the wireless device may determine the PUCCH resource based on at least the PUCCH resource indicator in a DCI (e.g., DCI format 1_0/1_1), from a list of PUCCH resources in a PUCCH resource set.

In an example embodiment, Listen-before-talk (LBT) may be implemented for transmission in a cell configured in unlicensed band (referred to as a LAA cell and/or a NR-U cell for the sake of convenience, for example, an LAA cell and NR-U cell may be interchangeable and may refer any cell operating in unlicensed band. The cell may be operated as non-standalone with an anchor cell in a licensed band or standalone without an anchor cell in licensed band). The LBT may comprise a clear channel assessment. For example, in an LBT procedure, equipment may apply a clear channel assessment (CCA) check before using the channel. For example, the CCA comprise at least energy detection that determines the presence (e.g., channel is occupied) or absence (e.g., channel is clear) of other signals on a channel. A regulation of a country may impact on the LBT procedure. For example, European and Japanese regulations mandate the usage of LBT in the unlicensed bands, for example in 5 GHz unlicensed band. Apart from regulatory requirements, carrier sensing via LBT may be one way for fair sharing of the unlicensed spectrum.

In an example embodiment, discontinuous transmission on an unlicensed carrier with limited maximum transmission duration may be enabled. Some of these functions may be supported by one or more signals to be transmitted from the beginning of a discontinuous downlink transmission in the unlicensed band Channel reservation may be enabled by the transmission of signals, by an NR-U node, after or in response to gaining channel access based on a successful LBT operation. Other nodes may receive the signals (e.g., transmitted for the channel reservation) with an energy level above a certain threshold that may sense the channel to be occupied. Functions that may need to be supported by one or more signals for operation in unlicensed band with discontinuous downlink transmission may comprise one or more of the following: detection of the downlink transmission in unlicensed band (including cell identification) by wireless devices; time and frequency synchronization of a wireless devices.

In an example embodiment, DL transmission and frame structure design for an operation in unlicensed band may employ subframe, (mini-)slot, and/or symbol boundary alignment according to carrier aggregation timing relationships across serving cells aggregated by CA. This may not imply that the base station transmissions start at the subframe, (mini-)slot, and/or symbol boundary. Unlicensed cell operation (e.g., LAA and/or NR-U) may support transmitting PDSCH, for example, when not all OFDM symbols are available for transmission in a subframe according to LBT. Delivery of necessary control information for the PDSCH may be supported.

An LBT procedure may be employed for fair and friendly coexistence of 3GPP system (e.g., LTE and/or NR) with other operators and technologies operating in unlicensed spectrum. For example, a node attempting to transmit on a carrier in unlicensed spectrum may perform a clear channel assessment (e.g., as a part of one or more LBT procedures) to determine if the channel is free for use. An LBT procedure may involve at least energy detection to determine if the channel is being used. For example, regulatory requirements in some regions, e.g., in Europe, specify an energy detection threshold such that if a node receives energy greater than this threshold, the node assumes that the channel is not free. While nodes may follow such regulatory requirements, a node may optionally use a lower threshold for energy detection than that specified by regulatory requirements. A radio access technology (e.g., LTE and/or NR) may employ a mechanism to adaptively change the energy detection threshold. For example, NR-U may employ a mechanism to adaptively lower the energy detection threshold from an upper bound. Adaptation mechanism may not preclude static or semi-static setting of the threshold. In an example Category 4 LBT (CAT4 LBT) mechanism or other type of LBT mechanisms may be implemented.

Various example LBT mechanisms may be implemented. In an example, for some signals, in some implementation scenarios, in some situations, and/or in some frequencies no LBT procedure may be performed by the transmitting entity. In an example, Category 1 (CAT1, e.g., no LBT) may be implemented in one or more cases. For example, a channel in unlicensed band may be hold by a first device (e.g., a base station for DL transmission), and a second device (e.g., a wireless device) takes over the for a transmission without performing the CAT1 LBT. In an example, Category 2 (CAT2, e.g. LBT without random back-off and/or one-shot LBT) may be implemented. The duration of time determining that the channel is idle may be deterministic (e.g., by a regulation). A base station may transmit an uplink grant indicating a type of LBT (e.g., CAT2 LBT) to a wireless device. CAT1 LBT and CAT2 LBT may be employed for COT sharing. For example, a base station may transmit an uplink grant (resp. uplink control information) comprising a type of LBT. For example, CAT1 LBT and/or CAT2 LBT in the uplink grant (or uplink control information) may indicate, to a receiving device (e.g., a base station, and/or a wireless device) to trigger COT sharing. In an example, Category 3 (CAT3, e.g. LBT with random back-off with a contention window of fixed size) may be implemented. The LBT procedure may have the following procedure as one of its components. The transmitting entity may draw a random number N within a contention window. The size of the contention window may be specified by the minimum and maximum value of N. The size of the contention window may be fixed. The random number N may be employed in the LBT procedure to determine the duration of time that the channel is sensed to be idle before the transmitting entity transmits on the channel. In an example, Category 4 (CAT4, e.g. LBT with random back-off with a contention window of variable size) may be implemented. The transmitting entity may draw a random number N within a contention window. The size of contention window may be specified by the minimum and maximum value of N. The transmitting entity may vary the size of the contention window when drawing the random number N. The random number N may be used in the LBT procedure to determine the duration of time that the channel is sensed to be idle before the transmitting entity transmits on the channel.

In an unlicensed band, a type of LBT (CAT1, CAT2, CAT3, and/or CAT4) may be configured via control messages (RRC, MAC CE, and/or DCI) per a cell. In an example, a type of LBT (CAT1, CAT2, CAT3, and/or CAT4) may be configured via control messages (RRC, MAC CE, and/or DCI) per BWP. For example, a type of LBT (CAT1, CAT2, CAT3, and/or CAT4) may be determined at least based on a numerology configured in a BWP. In this case, BWP switching may change a type of LBT.

In an example, a wireless device may employ uplink (UL) LBT. The UL LBT may be different from a downlink (DL) LBT (e.g. by using different LBT mechanisms or parameters) for example, since the NR-U UL may be based on scheduled access which affects a wireless device's channel contention opportunities. Other considerations motivating a different UL LBT comprise, but are not limited to, multiplexing of multiple wireless devices in a subframe (slot, and/or mini-slot).

In an example, DL transmission burst(s) may be a continuous (unicast, multicast, broadcast, and/or combination thereof) transmission by a base station (e.g., to one or more wireless devices) on a carrier component (CC). UL transmission burst(s) may be a continuous transmission from one or more wireless devices to a base station on a CC. In an example, DL transmission burst(s) and UL transmission burst(s) on a CC in an unlicensed spectrum may be scheduled in a TDM manner over the same unlicensed carrier. Switching between DL transmission burst(s) and UL transmission burst(s) may require an LBT (e.g., CAT1 LBT, CAT2 LBT, CAT3 LBT, and/or CAT4 LBT). For example, an instant in time may be part of a DL transmission burst and/or an UL transmission burst.

Channel occupancy time (COT) sharing may be employed in a radio access technology (e.g., LTE and or NR). COT sharing may be a mechanism that one or more wireless devices share a channel that is sensed as idle by at least one of the one or more wireless devices. For example, one or more first devices occupy a channel an LBT (e.g., the channel is sensed as idle based on CAT4 LBT) and one or more second devices shares it using an LBT (e.g., 25 us LBT) within a maximum COT (MCOT) limit. For example, the MOCT limit may be given per priority class, logical channel priority, and/or wireless device specific. COT sharing may allow a concession for UL in unlicensed band. For example, a base station may transmit an uplink grant to a wireless device for a UL transmission. For example, a base station may occupy a channel and transmit, to one or more wireless devices, a control signal indicating that the one or more wireless devices may use the channel. For example, the control signal may comprise an uplink grant and/or a particular LBT type (e.g., CAT1 LBT and/or CAT2 LBT). The one or more wireless device may determine COT sharing based at least on the uplink grant and/or the particular LBT type. The wireless device may perform UL transmission(s) with dynamic grant and/or configured grant (e.g., Type 1, Type2, autonomous UL) with a particular LBT (e.g., CAT2 LBT such as 25 us LBT) in the configured period, for example, if a COT sharing is triggered. A COT sharing may be triggered by a wireless device. For example, a wireless device performing UL transmission(s) based on a configured grant (e.g., Type 1, Type2, autonomous UL) may transmit an uplink control information indicating the COT sharing (UL-DL switching within a (M)COT). A starting time of DL transmission(s) in the COT sharing triggered by a wireless device may be indicated by one or more ways. For example, one or more parameters in the uplink control information indicate the starting time. For example, resource configuration(s) of configured grant(s) configured/activated by a base station may indicate the starting time. For example, a base station may be allowed to perform DL transmission(s) after or in response to UL transmission(s) on the configured grant (e.g., Type 1, Type 2, and/or autonomous UL). There may be a delay (e.g., at least 4 ms) between the uplink grant and the UL transmission. The delay may be predefined, semi-statically configured (via a RRC message) by a base station, and/or dynamically indicated (e.g., via an uplink grant) by a base station. The delay may not be accounted in the COT duration.

In an example, initial active DL/UL BWP may be 20 MHz (or approximately) for a first unlicensed band, e.g., in a 5 GHz unlicensed band. An initial active DL/UL BWP in one or more unlicensed bands may be similar (e.g., approximately 20 MHz in a 5 GHz and/or 6 GHz unlicensed spectrum), for example, if similar channelization is used in the one or more unlicensed bands (e.g., by a regulation). For a wideband case, a base station may configure a wideband with one or more BWP. For example, for 80 MHz case, a base station may configure four BWPs; each BWP may be configured with about 20 MHz. An active BWP (DL and/or UL) may be switched from one to another at least based on BWP switching mechanism. For example, a base station may configure the wideband with one or more subbands when the cell comprises a single BWP. For example, for 80 MHz case, a base station may configure four subbands; each subband may be configured with about 20 MHz. For example, a wireless device may perform an LBT subband by subband, and may transmit data via scheduled resources on one or more subbands where the LBT indicates idle.

In an example, carrier aggregation between PCell configured on a licensed band and SCell configured on unlicensed band may be supported. In an example, SCell may have both DL and UL, or DL-only. In an example, dual connectivity between PCell (e.g., LTE cell) configured on a licensed band and PSCell (e.g., NR-U cell) configured on unlicensed band may be supported. In an example, Stand-alone operation on an unlicensed band, where all carriers are in one or more unlicensed bands, may be supported. In an example, a cell with DL in unlicensed band and UL in a licensed band or vice versa may be supported. In an example, dual connectivity between PCell (e.g., NR cell) on a licensed band and PSCell (e.g., NR-U cell) on unlicensed band may be supported.

In an example, a radio access technology (e.g., LTE and/or NR) operating bandwidth may be an integer multiple of 20 MHz, for example, if absence of Wi-Fi cannot be guaranteed (e.g. by regulation) in an unlicensed band (e.g., 5 GHz, 6 GHZ, and/or sub-7 GHz) where the radio access technology (e.g., LTE and/or NR) is operating. In an example, a wireless device may perform one or more LBTs in units of 20 MHz. In an example, receiver assisted LBT (e.g., RTS/CTS type mechanism) and/or on-demand receiver assisted LBT (e.g., for example receiver assisted LBT enabled only when needed) may be employed. In an example, techniques to enhance spatial reuse may be used.

In an example, wideband carrier with more than one channels (e.g., subbands, SBs, RB sets) is supported on in an unlicensed band. In an example, there may be one active BWP in a carrier. A channel (a subband, RB set, etc.) may comprise a number of RBs within a BWP for data/control signal transmission. In this specification, a channel may be (equally) referred to as a subband, a SB, an RB set, etc. In an example, a BWP with one or more channels may be activated. In an example, when absence of Wi-Fi cannot be guaranteed (e.g. by regulation), LBT may be performed in units of 20 MHz. In this case, there may be multiple parallel LBT procedures for this BWP. The actual transmission bandwidth may be subject to SB with LBT success, which may result in dynamic bandwidth transmission within this active wideband BWP.

In an example, one or more active BWPs may be supported. To improve the BWP utilization efficiency, the BWP bandwidth may be the same as the bandwidth of SB for LBT, e.g., LBT may be carried out on each BWP. The network may activate/deactivate the BWPs based on data volume to be transmitted. In an example, one or more non-overlapped BWPs may be activated for a wireless device within a wide component carrier, which may be similar as carrier aggregation. To improve the BWP utilization efficiency, the BWP bandwidth may be the same as the bandwidth of SB for LBT, i.e. LBT may be a carrier out on each BWP. When LBT on more than one SB is successful, it requires a wireless device to have the capability to support one or more narrow RF or a wide RF which may comprise the one or more activated BWPs.

In an example, a single wideband BWP may be activated for a wireless device within a component carrier. The bandwidth of wideband BWP may be in the unit of SB for LBT. For example, if the SB for LBT is 20 MHz in 5 GHz band, the wideband BWP bandwidth may comprise multiple 20 MHz. The actual transmission bandwidth may be subject to SB with LBT success, which may result in dynamic bandwidth transmission within this active wideband BWP.

In an example, with wideband (e.g., 80 MHz) configuration on a BWP, frequency resources of a SS (or CORESET) may be spread (or across) within the BWP. Frequency resources of a SS (or CORESET) may be confined within a SB of the BWP. A SB may be in unit of 20 MHz, e.g., for LBT procedure in a NR-U cell. FIG. **27**A and FIG. **27**B show two SS/CORESET configurations in frequency domain in a BWP of a plurality of BWPs of a cell, or in a cell (in case of a single BWP configured on the cell).

FIG. **27**A shows an example of SS/CORESET configuration in a BWP. In an example, a frequency resource indication of 1^{st} SS or 1^{st} CORESET configuration may indicate frequency resources spread on a number of RB groups in the BWP, the number of RB groups not being confined or within a SB (e.g., 20 MHz) of the BWP. Spreading the frequency resources within the BWP may enable a base station to flexibly distribute PDCCH resources for different UEs, or different signalling purpose (e.g., common, or UE-specific).

FIG. **27**B show an example of SS/CORESET configuration in a BWP. In an example, a frequency resource indication of 1^{st} SS or 1^{st} CORESET configuration may indicate frequency resources are confined in a bandwidth (e.g., 20 MHz) of a first SB (SB 0 in FIG. **27**B) of the BWP. To maintain UE's capability of CORESETs/SSs configuration (e.g., at most 40 SSs per cell, or at most 12 or 20 CORESETs per cell) same (or similarly) as in case of operating in a licensed cell, a CORESET, identified by a CORESET ID, may be allocated with a same number of RBs (or RB groups) in each SB of the BWP. The same number of RBs (or RB groups) may be located in the same frequency locations (e.g., relative to a starting frequency location of each SB) of each SB of the BWP. As shown above, the pattern of mapping the CORESET to RBs of a SB may be replicated to the mapping of the CORESET to other SBs of the BWP.

In an example, a BWP may comprise a number (e.g., 4) of LBT SBs (SBs, or RB sets), each LBT SB occupying a number of RBs (or RB groups) of the BWP. A first LBT SB may overlap in frequency domain with a second LBT SB. A first LBT SB may not overlap in frequency domain with a second LBT SB.

In response to the frequency resource of 1^{st} CORESET being confined in a bandwidth of a SB of the BWP and be replicated to each SB of the BWP, the wireless device may monitor PDCCH on the 1^{st} SS of the 1^{st} CORESET on one or more SBs (e.g., SB 0, SB 1 in FIG. **27**B) of the number of SBs of the BWP, based on configuration or predefined rules. Confining frequency resources of a CORESET within a bandwidth of a SB of a BWP may increase signalling transmission robustness and/or save power consumption of the wireless device. In an example, a base station may perform LBT procedure per SB of the BWP. In response to the LBT procedure being successful on one of the SBs of the BWP, the base station may transmit DCI via a PDCCH on the one of the SBs of the BWP. In response to the LBT procedure being successful on more than one of the SBs of the BWP, the base station may transmit DCI via a PDCCH on the more than one of the SBs of the BWP, or the base station may transmit multiple DCI via PDCCH on the more than one of the SBs of the BWP, each DCI transmitted on a corresponding one of the more than one of the SBs.

In an example, a base station may allocate for a CORESET (e.g., in high layer parameter frequencyDomainResources of the CORESET in RRC messages, as shown in FIG. **24**) physical resource blocks (PRBs) confined within one of SBs of the BWP corresponding to the CORESET, for a search space set configuration associated with multiple monitoring locations in frequency domain. Within the search space set associated with the CORESET, each of the multiple monitoring locations in the frequency domain corresponds to (and/or is confined within) a SB of the SBs. Each of the multiple monitoring locations may have a frequency domain resource allocation pattern that is replicated from the pattern configured in the CORESET. In an example, CORESET parameters other than frequency domain resource allocation pattern may be identical for each of the multiple monitoring locations in the frequency domain.

In an example, a wireless device, before receiving a DCI, may not be aware of on which SB a base station may succeed an LBT procedure (e.g., when the LBT procedure indicates channel is clear on a SB), and may not be aware of on which

SB the base station may transmit the DCI. When configured with multiple LBT SBs on a BWP, the wireless device may monitor PDCCH on the multiple SBs for receiving the DCI.

In an example, a base station may transmit to a wireless device one or more RRC messages comprising configuration parameters of a search space, the configuration parameters indicating one or more SBs on which the wireless device may monitor PDCCH candidates of the search space. The wireless device may monitor PDCCH candidates associated with a search space on the one or more SBs based on the configuration parameters.

In existing technologies, a wireless device may index CCEs, from a first initial number (e.g., 0) to a second number (e.g., a maximum/total number configured on a CORESET), of radio resources of a CORESET on a BWP (or a cell when BWP is not configured on the cell), as shown in FIG. **25**B. The CCEs are across frequency resources of the BWP. The wireless device may monitor PDCCH candidates of a SS, for detecting a DCI, on one or more CCEs of the CCEs. The wireless device may receive the DCI on at least one CCE of the one or more CCEs. The wireless device may determine a starting CCE of the at least one CCE based on the CCE indexes, e.g., the starting CCE having a lowest CCE index among the at least one CCE. The wireless device may determine a PUCCH resource for HARQ-ACK feedback based on at least one of: a CCE index of the starting CCE of the at least one CCE on which the wireless device receives a DCI, the total number of CCEs and a PRI of the DCI.

In a NR-U cell (or a BWP of the cell), a wireless device may monitor a SS (or monitor PDCCH candidates of the SS) on one or more SBs of the BWP. In an example, the wireless device may receive a DCI on one of the one or more SBs, based on a LBT procedure at the base station, when at most one DCI is allowed to be transmitted for data scheduling in the BWP. The wireless device, by implementing existing technologies, may determine different PUCCH resources for UCI transmission when receiving a DCI on different SBs of the BWP. The wireless device, by implementing existing technologies, may determine PUCCH resource for transmitting UCI such that the base station needs to allocate (or reserve) PUCCH resources more than the wireless device actually utilizes to transmit the UCI. This may result in decreasing system throughput and/or reduced uplink resource utilization efficiency. The existing technologies may result in collision of UCI transmission on PUCCH (within the same wireless device, or among different wireless devices), decreasing system throughput, increasing uplink transmission latency, and/or increasing power consumption. Therefore, there is a need to improve PUCCH resource allocation method for a wideband NR-U to improve uplink resource utilization efficiency, system throughput, reduce collision of UCI transmission, reduce power consumption, etc.

In one of example embodiments, a wireless device may index CCEs of a CORESET, for each RB set of a BWP, from a same initial value (e.g., 0). In an example, the wireless device may index CCEs of the CORESET in a first RB set of the BWP from 0 to N−1, where N is a total number of CCEs of the CORESET in an RB set. The wireless device may index CCEs of the CORESET in a second RB set of the BWP from 0 to N−1. Based on indexing the CCEs of the CORESET from a same initial value for different RB sets of the BWP, the wireless device may determine a PUCCH resource based on: a CCE index of a starting CCE of one or more CCEs on which the wireless device receives a DCI, a PUCCH resource index indicated by the DCI, a total number of CCEs of the CORESET. Based on the example embodiment, the wireless device may select/determine a same PUCCH resource regardless of on which RB set the wireless device receives the DCI. Example embodiment may allow a base station to reduce PUCCH resource allocation/reservation for the wireless device and therefore improve uplink resource utilization efficiency.

FIG. **28** shows an example embodiment of PUCCH resource allocation/determination method for a wideband NR-U cell.

In an example, a base station may transmit a wireless device one or more RRC messages comprising configuration parameter of a cell (e.g., PCell, or SCell). The cell may comprise a plurality of BWPs. The cell may comprise a single BWP. In an example, a BWP may comprise a number (e.g., 4) of LBT SBs (SBs or RB sets which may be equally referred to as in this specification), each SB occupying a number of RBs (or RB groups) of the BWP. As shown in FIG. **28**, the SBs of the BWP comprise SB 0, SB 1, SB 2, and so on. The configuration parameters may indicate a plurality of CORESETs configured on a BWP. The configuration parameters may indicate that frequency resources of a CORESET of the plurality of CORESETs are confined in a bandwidth of a SB of the BWP. The frequency resource mapping pattern (e.g., defining on which resource blocks of the first SB the CORESET comprises, as shown by frequencyDomainResources in FIG. **24**) of the CORESET on the first SB is replicated to the rest SBs of the BWP. The configuration parameters may indicate a plurality of SSs are configured on a CORESET. For each SS of the plurality of SSs, the configuration parameters may comprise a monitoring frequency location parameter (e.g., a bitmap, or a monitoring location indication, as shown in FIG. **28**) indicating on which SB(s) a monitoring frequency location of the SS is configured. As shown in FIG. **28**, the monitoring location indication for a SS (e.g., SS_i) comprises a bit string "110 . . . ", indicating monitoring frequency location comprising SB 0, SB 1. In response to the monitoring frequency location comprising SB 0, SB 1, the wireless device may monitor SS_i on SB 0 and SB 1, and not monitor SS_i on the rest SBs (e.g., SB 2 and SB 3).

In an example, in response to monitoring SS_i on SB 0 and SB 1, the wireless device may attempt to detect DCI(s) on CCEs of SS_i on SB 0, and/or DCI(s) on CCEs of SS_i on SB1 (e.g., simultaneously, or sequentially). The wireless device may index CCEs, on different SBs of the BWP, from a same initial value (e.g., 0) to N−1 (e.g., N is a total number of CCEs in a SB). Based on the indexing the CCEs, the wireless device may attempt to detect first DCI on CCE 2, CCE 4, CCE 6, . . . on SB 0, and attempt to detect second DCI on CCE 2, CC 4, CCE 6, . . . on SB 1, where CC 2, CC 4, CC 6, . . . are determined for SS, by implementing examples of FIG. **25**B.

In an example, the wireless device may receive a first DCI on CCEs of SS_i on SB 0 of the BWP. The wireless device may receive a second DCI on CCEs of SS_i on SB 1 of the BWP. The wireless device may receive the first DCI and/or the second DCI based on LBT procedure performed by a base station on SB 0 and SB 1. In an example, the base station may transmit the first DCI on SB 0 when the base station determines a channel is clear on SB 0 based on a LBT procedure performed on SB 0. The base station may transmit the second DCI on SB 1 when the base station determines a channel is clear on SB 1 based on a LBT procedure performed on SB 1. Based on the indexing CCEs, on different SBs, from a same initial value, the wireless device may determine a first starting CCE, on SB 0, on which the first DCI is received, may have a same CCE index of a second starting CCE, on SB 1, on which the second DCI is received. The first DCI may indicate a same PRI value as the second DCI does.

In response to receiving a DCI (the first DCI or the second DCI), the wireless device may attempt to detect a TB based on downlink assignment of the DCI. The wireless device may determine an acknowledgement information for reception of the TB based on the detecting the TB. In an example, the wireless device may determine the acknowledgement information comprises a positive acknowledgment (ACK) for reception of the TB in response to the detecting the TB being successful. In an example, the wireless device may determine the acknowledgement information comprises a negative acknowledgment (NACK) for reception of the TB in response to the detecting the TB not being successful.

In an example, the wireless device may determine a PUCCH resource for transmitting the acknowledgement information, based on the starting CCE, a PRI of the DCI, by implementing example embodiment described above with respect to FIG. **25**A and/or FIG. **25**B. As shown in FIG. **28**, the starting CCE may have a CCE index equal to 2, regardless of on which SB the wireless device receives the DCI. By implementing example embodiment, the wireless device may determine the PUCCH resource, based on the CCE index of the starting CCE, wherein CCEs within a SB are indexed from a same initial value for each SB of the BWP. The wireless device may determine the PUCCH resource, based on the CCE index of the staring CCE, regardless on which SB the wireless device receives the DCI (the first DCI or the second DCI). Otherwise, based on existing technologies, the wireless device may determine different starting CCE index when receiving DCI on different SB, therefore the wireless device may determine different PUCCH resource for transmission of UCI based on the different starting CCE index. Example embodiment may allow the base station to reduce PUCCH resource allocation/reservation for the wireless device and therefore improve uplink resource utilization efficiency.

In a NR-U cell (or a BWP of the cell), a wireless device may monitor a SS (or monitor PDCCH candidates of the SS) on one or more SBs of the BWP. The wireless device may receive multiple DCIs on multiple SBs of the one or more SBs, each DCI being received via a search space of a CORESET on a respective SB of the one or more SBs. The wireless device may receive multiple DCIs on the multiple SBs when the base station succeeds LBT procedure on the multiple SBs. Receiving multiple DCIs on multiple SBs may increase system throughputs, e.g., when each DCI schedules a respective TB. The wireless device, based on existing technologies, may determine a same PUCCH resource for HARQ-ACK transmissions for different TBs scheduled by the multiple DCIs. This may result in collision of HARQ-ACK transmissions for different TBs. Therefore, existing technologies may result in collision of UCI transmission on PUCCH (within the same wireless device, or among different wireless devices), decreasing system throughput, increasing uplink transmission latency, and/or increasing power consumption. Therefore, there is a need to improve PUCCH resource allocation method for a wideband NR-U to improve uplink resource utilization efficiency, system throughput, reduce collision of UCI transmission, reduce power consumption, etc.

FIG. **29** shows an example of PUCCH resource determination mechanism when multiple PDCCH monitoring frequency locations on multiple SBs of a BWP are supported. In an example, a base station may transmit a wireless device one or more RRC messages comprising configuration parameter of a cell (e.g., PCell, or SCell). The cell may comprise a plurality of BWPs. The cell may comprise a single BWP. In an example, a BWP may comprise a number (e.g., 4) of SBs, each SB occupying a number of RBs (or RB groups) of the BWP. As shown in FIG. **29**, the SBs of the BWP comprise SB 0, SB 1, and so on. The configuration parameters may indicate a plurality of CORESETs configured on a BWP. The configuration parameters may indicate that frequency resources of a CORESET are confined in a bandwidth of a SB of the BWP. The configuration parameters may indicate a plurality of SSs are configured on a CORESET. For each SS of the plurality of SSs, the configuration parameters may comprise a monitoring frequency location parameter (e.g., a bitmap, or a monitoring location indication, as shown in FIG. **29**) indicating on which SB(s) a monitoring frequency location of the SS is configured. As shown in FIG. **29**, the monitoring location indication for a SS (e.g., SS_i) comprises a bit string "110 . . . ", indicating monitoring frequency location comprising SB 0, SB 1, wherein each bit of the bit string indicates whether a corresponding SB shall be monitored by the wireless device for the SS. In response to the monitoring frequency location comprising SB 0, SB 1, the wireless device may monitor SS_i on SB 0 and SB 1, and not monitor SS_i on other SBs of the BWP.

In an example, a wireless device may index CCE of each CCE of a SB based on at least one of: a SB index, and a total number of CCEs of a CORESET. In an example, a CORESET on SB 0 may comprise a same total number of CCEs on SB 1. In the example of FIG. **29**, the total number of CCEs of the CORESET is N. The wireless device may index CCEs of the CORESET on SB 0 from CCE 0 (or CCE 1) to CCE N−1 (or CCE N). The wireless device may index an i-th CCE of CCEs of the CORESET on SB j as: N*(j−1)+i, when i starts from 0. The wireless device may index an i-th CCE of CCEs of the CORESET on SB j as: N*(j−1)+1-1 when i starts from 1. In an example, an i-th CCE of CCEs on SB 0 and an i-th CCE of CCEs on SB j may have different CCE indexes. Having different CCE indexes on different SBs may allow a wireless device to reduce PUCCH resource collision.

In an example, a base station may transmit to a wireless device one or more RRC messages comprising configuration parameters of a BWP comprising a plurality of SBs, the configuration parameters indicating a CCE index offset (e.g., SB specific) for CCEs of a respective SB of the plurality of SBs. In an example, the configuration parameter may indicate a 1st CCE_index_offset for a 1st SB, a 2nd CCE_index_offset for 2nd SB, and so on. Based on the configuration parameters, the wireless device may index an i-th CCE on 1st SB as 1st CCE_index_offset+i, index an i-th CCE on 2nd SB as 2nd CCE_index_offset+i, and so on. The CCE index offset for each SB may be a cell specific parameter, or a UE specific parameter. The base station may transmit the CCE index offset in a system information in response to the CCE index offset being a cell specific parameter. The base station may transmit the CCE index offset in a UE specific cell configuration message in response to the CCE index offset being a UE specific parameter.

As shown in FIG. **29**, the wireless device may attempt to detect DCI(s) on CCEs on SB 0 and SB 1. In an example, the wireless device may attempt to detect first DCI on CCE 2, CCE 4, CCE 6, . . . on SB 0, where CC 2, CC 4, CC 6, are determined for SS_i by implementing examples of FIG. **25**B. The wireless device, based on monitoring CCE 2, CCE

4, CCE 6 . . . , may attempt to detect second DCI on CCE N+2, CC N+4, CCE N+6, . . . on SB 1.

As shown in FIG. **29**, the wireless device may receive a first DCI on CCEs of SS_i on SB 0 of the BWP. The wireless device may receive a second DCI on CCEs of SS_i on SB 1 of the BWP. A first starting CCE of the CCEs, on SB 0, on which the first DCI is received, may have a first CCE index (e.g., 2 as shown in FIG. **29**). A second starting CCE of the CCEs, on SB 1, on which the second DCI is received, may have a second CCE index (e.g., N+2 as shown in FIG. **29**). The first starting CCE and the second starting CCE, at a same location in order of CCE indexes on SB 0 and SB 1, may have different CCE indexes. In an example, the first DCI may indicate a same PRI value as the second DCI does.

In response to receiving the first DCI, the wireless device may attempt to detect a first TB based on first downlink assignment of the first DCI. The wireless device may determine a first acknowledgement information for reception of the first TB based on the detecting the first TB. In an example, the wireless device may determine the first acknowledgement information comprises a positive acknowledgment (ACK) for reception of the first TB in response to the detecting the first TB being successful. In an example, the wireless device may determine the first acknowledgement information comprises a negative acknowledgment (NACK) for reception of the first TB in response to the detecting the first TB not being successful.

In response to receiving the second DCI, the wireless device may attempt to detect a second TB (or the first TB in case of repetition) based on second downlink assignment of the second DCI. The wireless device may determine a second acknowledgement information for reception of the second TB based on the detecting the second TB. In an example, the wireless device may determine the second acknowledgement information comprises an ACK for reception of the second TB in response to the detecting the second TB being successful. In an example, the wireless device may determine the second acknowledgement information comprises a NACK for reception of the second TB in response to the detecting the second TB not being successful.

In an example, the wireless device may determine a first PUCCH resource for transmitting the first acknowledgement information, based on the first starting CCE, a first PM of the first DCI. The wireless device may determine a second PUCCH resource for transmitting the second acknowledgement information, based on the second starting CCE, a second PM of the first DCI.

In an example, when a wireless device does not have dedicated PUCCH resource configuration, the wireless device may determine the first PUCCH resource, r_{PUCCH}, based on the first starting CCE, a first PM of the first DCI, as

$$r_{PUCCH} = \left\lfloor \frac{2 \cdot n_{CCE,0}}{N'_{CCE}} \right\rfloor + 2 \cdot \Delta_{PRI},$$

where $N_{CCE}'=K*N_{CCE}$, N_{CCE} is a total number of CCEs in a CORESET on SB 0, K is a total number of SBs the wireless device is configured to monitor, $n_{CCE,0}$ is a CCE index of a first starting CCE for receiving the first DCI on SB 0, and Δ_{PRI} is a value of the PM field in the first DCI. In an example, K may be a maximum number of SBs configured on the BWP, or a predefined value (e.g., 4). As shown in FIG. **29**, the wireless device may determine the first PUCCH resource as PUCCH resource 2.

As shown in FIG. **29**, the wireless device may determine the second PUCCH resource, r_{PUCCH}, based on the second starting CCE, a second PRI of the second DCI, as

$$r_{PUCCH} = \left\lfloor \frac{2 \cdot n_{CCE,0}}{N'_{CCE}} \right\rfloor + 2 \cdot \Delta_{PRI},$$

where $N'_{CCE}=K*N_{CCE}$, N_{CCE} is a total number of CCEs in a CORESET on SB 1, K is a total number of SBs the wireless device is configured to monitor, $n_{CCE,0}$ is a CCE index of a second starting CCE for receiving the second DCI on SB 1, and Δ_{PRI} is a value of the PRI field in the second DCI. As shown in FIG. **29**, the wireless device may determine the second PUCCH resource as PUCCH resource 3.

In an example, when a wireless device has dedicated PUCCH resource configuration, the wireless device may determine the first PUCCH resource, r_{PUCCH} (e.g., $0 \le r_{PUCCH} \le R_{PUCCH}-1$), from a set of PUCCH resources (e.g., the first set when configured with multiple sets of PUCCH resources), based on the first starting CCE, a first PRI of the first DCI, as

$$r_{PUCCH} = \left\lfloor \frac{n_{CCE,p} \cdot \lfloor R_{PUCCH}/8 \rfloor}{N'_{CCE,p}} \right\rfloor + \Delta_{PRI} \cdot \left\lfloor \frac{R_{PUCCH}}{8} \right\rfloor + R_{PUCCH} \bmod 8$$

if $\Delta_{PRI} \ge R_{PUCCH} \bmod 8$

where $N'_{CCE,p}=K*N_{CCE,p}$, $N_{CCE,p}$ is a total number of CCEs in CORESET p on SB 0, K is a total number of SBs the wireless device is configured to monitor, $n_{ccE,p}$ is a CCE index of the first starting CCE in CORESET p for receiving the first DCI on SB 0, and Δ_{PRI} is a value of the PRI field in the first DCI. As shown in FIG. **29**, the wireless device may determine the first PUCCH resource as PUCCH resource 2.

In an example, the wireless device may determine the second PUCCH resource, r_{PUCCH} (e.g., $0 \le r_{PUCCH} \le R_{PUCCH}-1$) based on the second starting CCE, a second PRI of the second DCI, as

$$r_{PUCCH} = \left\lfloor \frac{n_{CCE,p} \cdot \lfloor R_{PUCCH}/8 \rfloor}{N'_{CCE,p}} \right\rfloor + \Delta_{PRI} \cdot \left\lfloor \frac{R_{PUCCH}}{8} \right\rfloor + R_{PUCCH} \bmod 8$$

if $\Delta_{PRI} \ge R_{PUCCH} \bmod 8$

where $N'_{CCE,p}=K*N_{CCE,p}$, $N_{CCE,p}$ is a total number of CCEs in CORESET p on SB 1, K is a total number of SBs the wireless device is configured to monitor, $n_{CCE,p}$ is a CCE index of the second starting CCE in CORESET p for receiving the second DCI on SB 1, and Δ_{PRI} is a value of the PRI field in the second DCI. As shown in FIG. **29**, the wireless device may determine the second PUCCH resource as PUCCH resource 3.

As shown in FIG. **29**, the wireless device may determine different PUCCH resources for ACK/NACK transmission for different TBs. By example embodiments, the wireless device may reduce PUCCH transmission collision, and improve uplink transmission latency, system throughput.

In an example, the wireless device may index CCEs of a SB of a plurality of SBs on a BWP independently and separately. The CCE indexes may be reused on different SBs. In an example, the wireless device may index CCEs of a first SB from CCE 0 to CCE N−1, and index CCEs of a second SB from CCE 0 to CCE N−1. Reusing CCE indexes on different SBs may improve UE's implementation complexity, and/or backward compatibility.

In an example, when the wireless device reuses CCE indexes on different SBs, the wireless device may determine a PUCCH resource, r_{PUCCH}, based on a starting CCE, a SB index of a SB (e.g., SB 0 or SB 1), a PM of a DCI received on the SB, as

$$r_{PUCCH} = \left\lfloor \frac{2 \cdot n_{CCE,0} + \text{SB\_index} * N_{CCE}}{N'_{CCE}} \right\rfloor + 2 \cdot \Delta_{PRI},$$

where $N'_{CCE}=K*N_{CCE}$, N_{CCE} is a total number of CCEs in a CORESET on the SB, K is a total number of SBs the wireless device is configured to monitor, $n_{CCE,0}$ is a CCE index of the starting CCE for receiving the DCI on the SB, SB_index is a SB index of the SB on which the wireless device receives the DCI, and Δ_{PRI} is a value of the PRI field in the DCI.

In an example, when the wireless device reuses CCE indexes on different SBs, the wireless device may determine a PUCCH resource, r_{PUCCH} (eg, $0 \le r_{PUCCH} \le R_{PUCCH}-1$), from a set of PUCCH resources (e.g., the first set when configured with multiple sets of PUCCH resources), based on a starting CCE, a SB index of a SB (e.g., SB 0 or SB 1), and/or a PM of a DCI received on the SB. In an example, the wireless device may determine r_{PUCCH} as

$$r_{PUCCH} = SB\_index + \left\lfloor \frac{n_{CCE,p} \cdot \lfloor R_{PUCCH}/8 \rfloor}{N'_{CCE,p}} \right\rfloor + \Delta_{PRI} \cdot \left\lfloor \frac{R_{PUCCH}}{8} \right\rfloor + R_{PUCCH} \bmod 8$$

if $\Delta_{PRI} \ge R_{PUCCH} \bmod 8$

where $N'_{CCE,p}=K*C_{CCE,p}$, $N_{CCE,p}$ is a total number of CCEs in CORESET p on the SB, K is a total number of SBs the wireless device is configured to monitor, $n_{CCE,p}$ is a CCE index of the starting CCE in CORESET p for receiving the DCI on the SB, SB_index is a SB index of the SB on which the wireless device receives the DCI, and Δ_{PRI} is a value of the PM field in the DCI. In an example, when the total number of SBs are greater than 2, SB_index may be modeled by

$$\left\lfloor \frac{R_{PUCCH}}{8} \right\rfloor.$$

FIG. **30** shows an example flowchart of PUCCH resource determination mechanism. In an example, a base station may transmit to a wireless device one or more RRC messages comprising configuration parameters of a cell (not shown in FIG. **30**). The cell may comprise a plurality of BWPs. A BWP, of the plurality of BWPs, may comprise a plurality of SBs. In an example, the base station may transmit to a wireless device a command (e.g., a DCI) indicating an activation of a BWP. In response to receiving the command, the wireless device may activate the BWP. The wireless device may, in response to activating the BWP, monitor a SS of a CORESET on a first SB and a second SB, monitoring the first SB and the second SB being indicated in the configuration parameters. The base station may perform LBT procedure on the first SB and the second SB sequentially or simultaneously.

In an example, the base station may determine LBT procedure on the first SB indicates a clear channel on the first SB. In response to LBT procedure indicating a clear channel on the first SB, the base station may transmit to the wireless device a first DCI via the first SB, the first DCI indicating a first downlink radio resource for downlink assignment for transmission of a first TB and a first PUCCH resource for ACK/NACK transmission for the first TB. In an example, the base station may determine LBT procedure on the second SB indicates a clear channel on the second SB. In response to LBT procedure indicating a clear channel on the second SB, the base station may transmit to the wireless device a second DCI via the second SB, the second DCI indicating a second downlink radio resource for downlink assignment for transmission of a second TB (or the first TB in case of repetition) and a second PUCCH resource for ACK/NACK transmission for the second TB.

In an example, the wireless device may receive the first DCI during monitoring the SS of the CORESET on the first SB, and receive the second DCI during monitoring the SS of the COREST on the second SB. The wireless device may, based on receiving the first DCI, detect the first TB via the first downlink radio resource on the first SB, and determine a first acknowledgement information for detection of the first TB. The wireless device may, based on receiving the second DCI, detect the second TB via the second downlink radio resource on the second SB, and determine a second acknowledgement information for detection of the second TB.

In an example, the wireless device may determine a first PUCCH resource, for transmission of the first acknowledgement information, based on: a first CCE index of a starting CCE of CCEs of the CORESET for receiving the first DCI, a SB index of the first SB, and/or a PRI value indicated in the first DCI. In an example, the wireless device may determine a second PUCCH resource, for transmission of the second acknowledgement information, based on: a second CCE index of a starting CCE of CCEs of the CORESET for receiving the second DCI, a SB index of the second SB, and/or a PRI value indicated in the second DCI. The wireless device may determine the first PUCCH resource and/or the second PUCCH resource by implementing examples of FIG. **29**. The wireless device my transmit the first acknowledgement for reception of the first TB via the first PUCCH resource. The wireless device may transmit the second acknowledgement for reception of the second TB via the second PUCCH resource.

FIG. **31** shows an example of PUCCH configuration when multiple SBs are supported in a NR-U system. In an example, a base station may transmit a wireless device one or more RRC messages comprising configuration parameter of a cell (e.g., PCell, or SCell). The cell may comprise a plurality of BWPs. The cell may comprise a single BWP. In an example, a BWP may comprise a number (e.g., 4) of SBs, each SB occupying a number of RBs (or RB groups) of the BWP. As shown in FIG. **31**, the SBs of the BWP comprise SB 0, SB 1, SB 2, and so on. The configuration parameters may indicate a plurality of CORESETs configured on a BWP. The configuration parameters may indicate that frequency resources of a CORESET are confined in a bandwidth of a SB of the BWP. The configuration parameters may indicate a plurality of SSs are configured on a CORESET. For each SS of the plurality of SSs, the configuration parameters may comprise a monitoring frequency location parameter (e.g., a bitmap, or a monitoring location indication, as shown in FIG. **31**) indicating on which SB(s) a monitoring frequency location of the SS is configured. As shown in FIG. **31**, the monitoring location indication for a SS (e.g., SS_i) comprises a bit string "110 . . . ", indicating monitoring frequency location comprising SB 0, SB 1. In response to the monitoring frequency location comprising SB 0, SB 1, the wireless device may monitor SS_i on SB 0 and SB 1, and not monitor SS_i on other SBs of the BWP.

In an example, the wireless device may index CCEs of a SB of a plurality of SBs on a BWP independently and separately. The CCE indexes may be reused on different SBs. In an example, the wireless device may index CCEs of a first SB (e.g., SB 0) from CCE 0 to CCE N−1, and index CCEs of a second SB (e.g., SB 1) from CCE 0 to CCE N−1. Reusing CCE indexes on different SBs may improve UE's implementation complexity, and/or backward compatibility.

In an example, a base station may transmit to a wireless device one or more RRC messages comprising configuration parameters of PUCCH resource configuration on a first BWP on a PCell or a PUCCH SCell. In an example, the configuration parameters of the PUCCH resource configuration may indicating a plurality of PUCCH resource sets. Each PUCCH resource set of the plurality of PUCCH resource sets may comprise a number of PUCCH resources. In an example, the configuration parameters may indicate a first subset of the number of PUCCH resources, of a PUCCH resource set, correspond to a first SB of a plurality of SBs of a BWP of a cell (e.g., PCell or SCell), a second subset of the number of PUCCH resources correspond to a second SB of the plurality of SBs of the BWP of the cell, and so on. As shown in FIG. **31**, PUCCH resources of a PUCCH resource set may comprise PUCCH resources with PUCCH resource index 0, 1, 2, 3, 4, . . . , K−1, K+1 . . . , and M. K may be a total number of PUCCH resources for a first SB. M may be a total number of the PUCCH resources in the PUCCH resource set. K and/or M may be indicated in the one or more RRC messages. In an example, the configuration parameters may indicate PUCCH resources with PUCCH resource index 0, 1, . . . K−1 correspond to (or are associated with) the first SB. The configuration parameters may indicate PUCCH resources with PUCCH resource index K, K+1, . . . 2K−1 correspond to (or are associated with) the second SB. In an example, the total number of PUCCH resources (e.g., K) for the first SB may be different from the total number (e.g., J) of PUCCH resources for the second SB, where K and J are indicated in the one or more RRC messages or are set to predefined values (e.g., 8, 16, 32, and any number greater than zero).

In an example, a base station may transmit to a wireless device one or more RRC messages comprising configuration parameters of PUCCH resource configuration on a first BWP on a PCell or a PUCCH SCell. In an example, the configuration parameters of the PUCCH resource configuration may indicating a plurality of PUCCH resource sets. Each PUCCH resource set of the plurality of PUCCH resource sets may comprise a number of PUCCH resources. In an example, the configuration parameters may indicate a first PUCCH resource index offset corresponds to a first SB of a plurality of SBs of a BWP of a cell (e.g., PCell or SCell), a second PUCCH resource index offset corresponds to a second SB of the plurality of SBs of the BWP of the cell, and so on. In an example, based on receiving the one or more RRC messages, the wireless device may determine a first PUCCH resource, for the first acknowledgement information for reception of the first TB via the first SB, based on at least one of: the first PUCCH resource index offset, a CCE index of a starting CCE for receiving the first DCI, a PRI value indicated in the first DCI. In an example, based on receiving the one or more RRC messages, the wireless device may determine a second PUCCH resource, for the second acknowledgement information for reception of the second TB via the second SB, based on at least one of: the second PUCCH resource index offset, a CCE index of a starting CCE for receiving the second DCI, a PRI value indicated in the second DCI.

As shown in FIG. **31**, the wireless device may attempt to detect DCI(s) on CCEs on SB 0 and SB 1. In an example, the wireless device may attempt to detect first DCI on CCE 2, CCE 4, CCE 6, . . . on SB 0, where CC 2, CC 4, CC 6, are determined for SS_i by implementing examples of FIG. **25**B. The wireless device, based on monitoring CCE 2, CCE 4, CCE 6 . . . , may attempt to detect second DCI on CCE 2, CC 4, CCE 6, . . . on SB 1.

As shown in FIG. **31**, the wireless device may receive a first DCI on CCEs of SS_i on SB 0 of the BWP. The wireless device may receive a second DCI on CCEs of SS_i on SB 1 of the BWP. A first starting CCE of the CCEs, on SB 0, on which the first DCI is received, may have a same CCE index (e.g., 2 as shown in FIG. **31**) as a second starting CCE of the CCEs, on SB 1, on which the second DCI is received. A first starting CCE of the CCEs, on SB 0, on which the first DCI is received, may have a different CCE index from a second starting CCE of the CCEs, on SB 1, on which the second DCI is received. In an example, the first DCI may indicate a same PRI value as the second DCI does.

In an example, the wireless device may, based on receiving the first DCI, detect the first TB via the first downlink radio resource on the first SB, and determine a first acknowledgement information for detection of the first TB. The wireless device may, based on receiving the second DCI, detect the second TB via the second downlink radio resource on the second SB, and determine a second acknowledgement information for detection of the second TB.

In an example, the wireless device may determine a first PUCCH resource, from a first subset of PUCCH resources (e.g., PUCCH resources with PUCCH resource indexes 0, 1, 2, . . . K−1 as shown in FIG. **31**), corresponding to the first SB, of the PUCCH resource set, for transmitting the first acknowledgement information, based on the first starting CCE, a first PRI of the first DCI. The wireless device may determine a second PUCCH resource, from a second subset of PUCCH resources (e.g., PUCCH resources with PUCCH resource indexes K, K+1, K+2, . . . 2*K−1 as shown in FIG. **31**), corresponding to the second SB, of the PUCCH resource set, for transmitting the second acknowledgement information, based on the second starting CCE, a second PRI of the first DCI. The wireless device may determine the first PUCCH resource from the first subset of PUCCH resources by implementing example embodiments of FIG. **25**B. The wireless device may determine the second PUCCH resource from the second subset of PUCCH resources by implementing example embodiments of FIG. **25**B.

As shown in FIG. **31**, the wireless device may determine different PUCCH resources, from different PUCH resource subsets corresponding to different SBs, for ACK/NACK transmission for different TBs. By example embodiments, the wireless device may reduce PUCCH transmission collision, and improve uplink transmission latency, system throughput.

Example embodiments of FIG. **28**, FIG. **29** and/or FIG. **31** may be implemented based on configuration. In an example, when a wireless device and a base station supports at most one DCI for data scheduling on multiple RB sets of a BWP, the base station and the wireless device may perform PUCCH resource determination method based on example of FIG. **28**. When a wireless device and a base station supports multiple DCIs for data scheduling on multiple RB sets of a BWP and uplink channel is heavily loaded, the base station and the wireless device may perform PUCCH resource determination method based on example of FIG. **29**. When a wireless device and a base station supports multiple DCIs for data scheduling on multiple RB sets of a BWP and uplink channel is not heavily loaded, the base station and the wireless device may perform PUCCH resource determination method based on example of FIG. **31**.

In an example, a first DL SB of a plurality of DL SBs may be linked to a first UL SB of a plurality of UL SBs. The plurality of DL SBs may be comprised in a DL BWP of a cell. The plurality of UL SBs may be comprised in an UL BWP of the cell. In an example, a wireless device may receive a DCI via a first DL SB of the plurality of DL SBs. The wireless device may, based on linkage between the first DL SB and the first UL SB, determine a PUCCH resource on the first UL SB, for ACK/NACK transmission.

In an example, a first wireless device may select a first UL SB from a plurality of UL SBs of a BWP for PUCCH transmission of ACK/NACK, based on a selection priority. The selection priority may be indicated by an RRC message. The selection priority may be predefined. The selection priority may indicate an order of UL SB selection from the plurality of UL SBs. In an example, different UEs may be configured with different selection priorities. Configuring different selection priorities may improve PUCCH collisions.

In an example, a wireless device may monitor a PDCCH on CCEs of a SB of a plurality of SBs of a BWP of a cell. The wireless device may receive, via the PDCCH on one or more CCEs of the CCEs, a DCI comprising a radio resource indication and a PUCCH resource index. The wireless device may receive a TB via a radio resource indicated by the radio resource indication. The wireless device may determine a PUCCH resource based on at least one of: the PUCCH resource index, a SB index of the SB, and/or a CCE index of a starting CCE of the one or more of the CCEs. The wireless device may transmit, via the PUCCH resource, an acknowledgement information for reception of the TB. The wireless device may further receive one or more RRC messages comprising configuration parameters of a cell comprising a plurality of BWPs, each of the plurality of BWPs comprising a plurality of SBs. Each of the plurality of SBs may be identified with a respective SB index. The configuration parameters of the cell may further comprise first configuration parameters of a BWP of the plurality of BWPs, the first configuration parameters comprising one or more radio resource configuration parameters of a CORESET. The one or more radio resource configuration parameters of the CORESET may indicate that frequency resources of the CORESET are confined in a bandwidth of a SB of the BWP. The one or more radio resource configuration parameters may indicate that a search space, associated with the CORESET, is configured with one or more monitoring frequency location indication. Each frequency location indication, corresponding to a respective SB of one or more SBs of the plurality of SBs, may indicate whether the wireless device monitors PDCCH for the search space on the SB. The frequency resources of the CORESET on a SB may comprise a plurality of CCEs, each of the plurality of CCEs being identified with a CCE index. CCE index of a first CCE of the plurality of CCE may start from a first predefined value (e.g., 0, or 1).

In an example, the wireless device may monitor a PDCCH on the search space on a SB of the plurality of SBs, in response to a monitoring frequency location indication, corresponding to the SB, indicating PDCCH monitoring on the SB for the search space.

In an example, the one or more RRC messages may further indicate a plurality of PUCCH resource sets, each of the PUCCH resource set comprising a plurality of PUCCH resources. Each of the plurality of PUCCH resources may be identified with a respective PUCCH resource index. The wireless device may determine the PUCCH resource from the plurality of PUCCH resources of one of the plurality of PUCCH resource sets.

In an example, the acknowledgement information may comprise a positive acknowledgement (ACK) in response to reception of the TB being successful. The acknowledgement information may comprise a negative acknowledgement (NACK) in response to reception of the TB not being successful.

In an example, the wireless device may monitor a second PDCCH on CCEs of a second SB of the plurality of SB. The wireless device may receive, via the second PDCCH on one or more CCEs of the CCEs, a second DCI comprising a second radio resource indication and a second PUCCH resource index. The wireless device may receive a second TB via a second radio resource indicated by the second radio resource indication. The wireless device may determine a second PUCCH resource based on at least one of: the second PUCCH resource index, a second SB index of the second SB, and/or a second CCE index of a second starting CCE of the one or more of the CCEs. The wireless device may transmit, via the second PUCCH resource, a second acknowledgement information for reception of the second TB.

In an example, the second PUCCH resource may be different from the PUCCH resource. The second SB index may be different from the SB index.

In an example, a wireless device may monitor a PDCCH on CCEs of a SB of a plurality of SBs. The wireless device may receive, via the PDCCH on one or more CCEs of the CCEs, a DCI comprising a radio resource indication and a PUCCH resource index. The wireless device may receive a TB via a radio resource indicated by the radio resource indication. The wireless device may determine a PUCCH resource based on at least one of: the PUCCH resource index, a PUCCH resource index offset associated with the SB, and/or a CCE index of a starting CCE of the one or more of the CCEs. The wireless device may transmit, via the PUCCH resource, an acknowledgement information for reception of the TB.

In an example, a wireless device may receive configuration parameters indicating a respective CCE index offset for a corresponding SB of a plurality of SBs. The wireless device may monitor a PDCCH on CCEs of a SB of a plurality of SBs. The wireless device may receive, via the PDCCH on one or more CCEs of the CCEs, a DCI comprising a radio resource indication and a PUCCH resource index. The wireless device may receive a TB via a radio resource indicated by the radio resource indication. The wireless device may determine a PUCCH resource based on at least one of: the PUCCH resource index, a respective CCE index offset corresponding to the SB, and a CCE index of a starting CCE of the one or more of the CCEs. The wireless device may transmit, via the PUCCH resource, an acknowledgement information for reception of the TB.

FIG. **32** shows a flow diagram as per an aspect of an example embodiment of the present disclosure. At **3210**, a wireless device may receive configuration parameters of a BWP comprising RB sets, wherein CCEs of a CORESET of the BWP are across the RB sets and a subset of the CCEs, within each RB set of the RB sets, are indexed from a same initial value. At **3220**, the wireless device may receive a DCI via one or more CCEs of the subset of the CCEs within an RB set of the RB sets. At **3230**, the wireless device may determine, a CCE index of a starting CCE of the one or more CCEs, based on indexing the subset of the CCEs from the initial value within the RB set. At **3240**, the wireless device may transmit an uplink signal via an uplink resource determined based on the CCE index.

FIG. **33** shows a flow diagram as per an aspect of an example embodiment of the present disclosure. At **3310**, a wireless device may receive configuration parameters of a BWP comprising RB sets, wherein CCEs are across the RB sets and a subset of the CCEs, within each RB set of the RB sets, are indexed from a same initial value. At **3320**, the wireless device may receive a control information via one or more CCEs of the subset of the CCEs within an RB set of the RB sets. At **3330**, the wireless device may transmit an uplink signal via an uplink resource based on an index of a CCE of the one or more CCEs.

According to an example embodiment, the wireless device may receive one or more RRC messages comprising second configuration parameters of a cell, wherein the cell comprises a plurality of bandwidth parts comprising the bandwidth part.

According to an example embodiment, the initial value may be zero. The control information may a DCI via a PDCCH on the one or more CCEs.

According to an example embodiment, each CCE of the CCEs may comprise a number of resource element groups, wherein a resource-element group comprises an RB in a symbol.

According to an example embodiment, each RB set of the RB sets may comprise one or more RBs of the bandwidth part. Each RB of the one or more RBs may comprise a number of resource elements of the bandwidth part. The first RB set may comprise one or more RBs non-overlapping with a second RB set of the RB sets.

According to an example embodiment, the configuration parameters may indicate that a control resource set of the bandwidth part comprises the CCEs. The configuration parameters may indicate that a frequency domain resource allocation pattern of the control resource set is replicated for each RB set of the RB sets of the bandwidth part, wherein physical radio resources of the CCEs of the control resource set are mapped to each RB set. The wireless device may determine the uplink resource further based on a total number of the first subset of the CCEs, within the first RB set, associated with the control resource set.

According to an example embodiment, the configuration parameters may indicate one or more RB sets comprising the first RB set, from the RB sets of the bandwidth part, for a search space associated with the control resource set. The search space may comprise the one or more CCEs of the first subset of the CCEs associated with the control resource set within the first RB set. The search space, associated with the control resource set, may be configured with one or more monitoring frequency location indications, each frequency location indication corresponding to a respective RB set of the RB sets of the bandwidth part. The wireless device may monitor a downlink control channel on the search space on the first RB set, in response to a monitoring frequency location indication, corresponding to the first RB set, indicating downlink control channel monitoring on the first RB set. The wireless device may receive the control information during the monitoring the downlink control channel on the search space.

According to an example embodiment, the uplink resource may comprise a physical uplink control channel (PUCCH) resource.

According to an example embodiment, the configuration parameters may indicate a plurality of PUCCH resources. Each of the plurality of PUCCH resources may be identified with a respective PUCCH resource index. Each of the plurality of PUCCH resources may be associated with an RB set index of an RB set of the RB sets. The wireless device may transmit the signal via the uplink resource associated with the first RB set. The control information may comprise a PUCCH resource indication field indicating a PUCCH resource index. The wireless device may determine the uplink resource further based on the PUCCH resource index indicated by the control information.

According to an example embodiment, the wireless device may determine the uplink resource based on a PUCCH resource index indicated by the control information and a PUCCH resource index offset determined based on the index of the CCE.

According to an example embodiment, the control information may comprise downlink assignment of downlink radio resource for transmitting a transport block. The wireless device may receive the transport block via the downlink radio resource based on the control information.

According to an example embodiment, the signal may comprise an acknowledgement information corresponding to a transport block scheduled by the control information. The acknowledgement information may comprise a positive acknowledgement (ACK) in response to reception of the transport block being successful. The acknowledgement information may comprise a negative acknowledgement (NACK) in response to reception of the transport block not being successful.

According to an example embodiment, the CCE may be a starting CCE (e.g., with the lowest CCE index) of the one or more CCEs based on indexing the first subset of the CCEs from the initial value within the first RB set. The wireless device may determine the uplink resource based on a PUCCH resource indicator in the downlink control information and a PUCCH resource offset determined based on the index of the starting CCE.

FIG. **34** shows a flow diagram as per an aspect of an example embodiment of the present disclosure. At **3410**, a wireless device may monitor a downlink control channel on control channel elements (CCEs) of a resource block (RB) set of RB sets of a bandwidth part. At **3420**, the wireless device may receive, on one or more CCEs of the CCEs, a downlink control information comprising a physical uplink control channel (PUCCH) resource index. At **3430**, the wireless device may transmit an uplink signal via a PUCCH resource determined based on the PUCCH resource index, an RB set index of the RB set and a CCE index of a starting CCE of the one or more CCEs.

What is claimed is:

1. A method, comprising:

transmitting configuration parameters of a control resource set,

wherein a bandwidth part comprises the control resource set, and

wherein the control resource set comprises a plurality of resource blocks;

transmitting a control information via a first control channel element of at least one control channel element, wherein a first resource block of the plurality of resource blocks comprises the first control channel element; and

receiving a signal via an uplink resource based on an index of the first control channel element,

wherein the index starts from an initial value, and

wherein the initial value is the same as starting index values of control channel elements within each resource block of the plurality of resource blocks.

2. The method of claim **1**,

wherein the initial value is zero, and

wherein the starting index values of the control channel elements within each resource block of the plurality of resource blocks, are in an ascending order.

3. The method of claim **1**,

wherein the configuration parameters indicate that a frequency domain resource allocation pattern of the control resource set is replicated for each resource block of the plurality of resource blocks, and

wherein physical radio resources of the control channel elements are mapped to the plurality of resource blocks.

4. The method of claim **3**,

wherein the control resource set is associated with the first control channel element, and

wherein the uplink resource is based on a total number of the first control channel element.

5. The method of claim **1**,

wherein the configuration parameters indicate a portion of the plurality of resource blocks,

wherein the portion comprises the first resource block of a search space associated with the control resource set, and

wherein the search space comprises the first control channel element.

6. The method of claim **5**,

wherein the search space is configured with at least one monitoring frequency location indications, and

wherein each of the at least one monitoring frequency location indications corresponds to a resource block of the plurality of resource blocks.

7. The method of claim **1**,

wherein the uplink resource is based on a physical uplink control channel resource index indicated by the control information; and a physical uplink control channel resource index offset, and

wherein the physical uplink control channel resource index offset is determined based on the index of the first control channel element.

8. The method of claim **1**, wherein the first control channel element is a starting control channel element of the at least one control channel elements.

9. A device, comprising:

a processor circuit; and

a memory circuit, wherein the memory circuit is arranged to store instructions for the processor circuit,

wherein the processor circuit is arranged to transmit configuration parameters of a control resource set,

wherein a bandwidth part comprises the control resource set,

wherein the control resource set comprises a plurality of resource blocks,

wherein the processor circuit is arranged to transmit a control information via a first control channel element of an at least one control channel element,

wherein a first resource block of the plurality of resource blocks comprises the first control channel element,

wherein the processor circuit is arranged to receive a signal via an uplink resource based on an index of the first control channel element,

wherein the index starts from an initial value, and

wherein the initial value is the same as starting index values of control channel elements within each resource block of the plurality of resource blocks.

10. The device of claim **9**,

wherein the initial value is zero, and

wherein the starting index values of the control channel elements within each resource block of the plurality of resource blocks, are in an ascending order.

11. The device of claim **9**,

wherein the configuration parameters indicate that a frequency domain resource allocation pattern of the control resource set is replicated for each resource block of the plurality of resource blocks, and

wherein physical radio resources of the control channel elements are mapped to the plurality of resource blocks.

12. The device of claim **11**,

wherein the control resource set is associated with the first control channel element, and

wherein the uplink resource is based on a total number of the first control channel element.

13. The device of claim **9**,

wherein the configuration parameters indicate a portion of the plurality of resource blocks,

wherein the portion comprises the first resource block of a search space associated with the control resource set, and

wherein the search space comprises the first control channel element.

14. The device of claim **13**,

wherein the search space is configured with at least one monitoring frequency location indication, and

wherein each of the at least one monitoring frequency location indications corresponds to a resource block of the plurality of resource blocks.

15. The device of claim **9**,

wherein the uplink resource is based on a physical uplink control channel resource index indicated by the control information and a physical uplink control channel resource index offset, and

wherein the physical uplink control channel resource index offset is determined based on the index of the first control channel element.

16. The device of claim **9**, wherein the first control channel element is a starting control channel element of the at least one control channel element.

17. A non transitory computer-readable medium, wherein the non-transitory computer-readable medium has stored therein a computer program, wherein the computer program when executed on a processor performs:

transmitting configuration parameters of a control resource set,

wherein a bandwidth part comprises the control resource set, and

wherein the control resource set comprises a plurality of resource blocks;

transmitting a control information via a first control channel element of at least one control channel element, wherein a first resource block of the plurality of resource blocks comprises the first control channel element; and

receiving a signal via an uplink resource based on an index of the first control channel element,

wherein the index starts from an initial value, and

wherein the initial value is the same as starting index values of control channel elements within each resource block of the plurality of resource blocks.

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